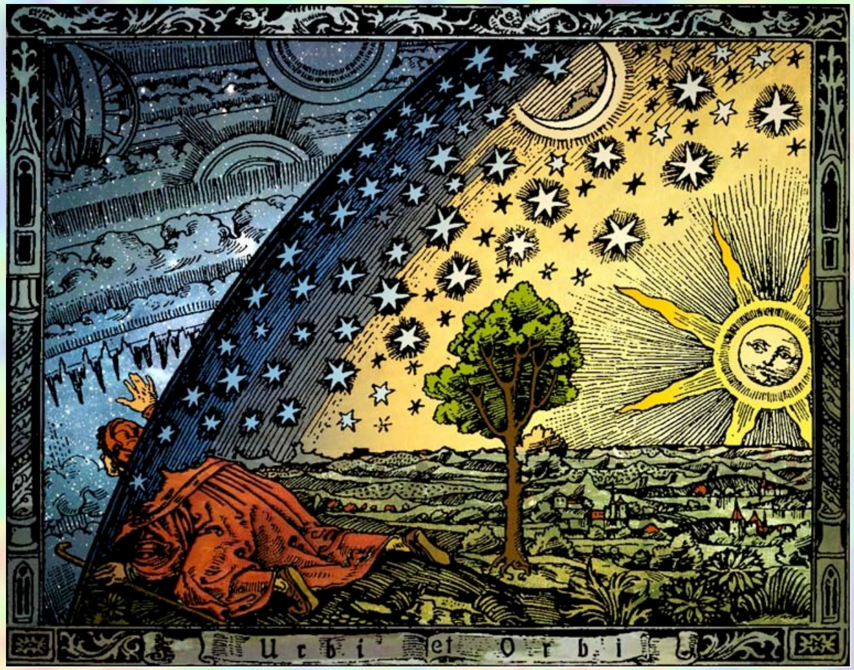
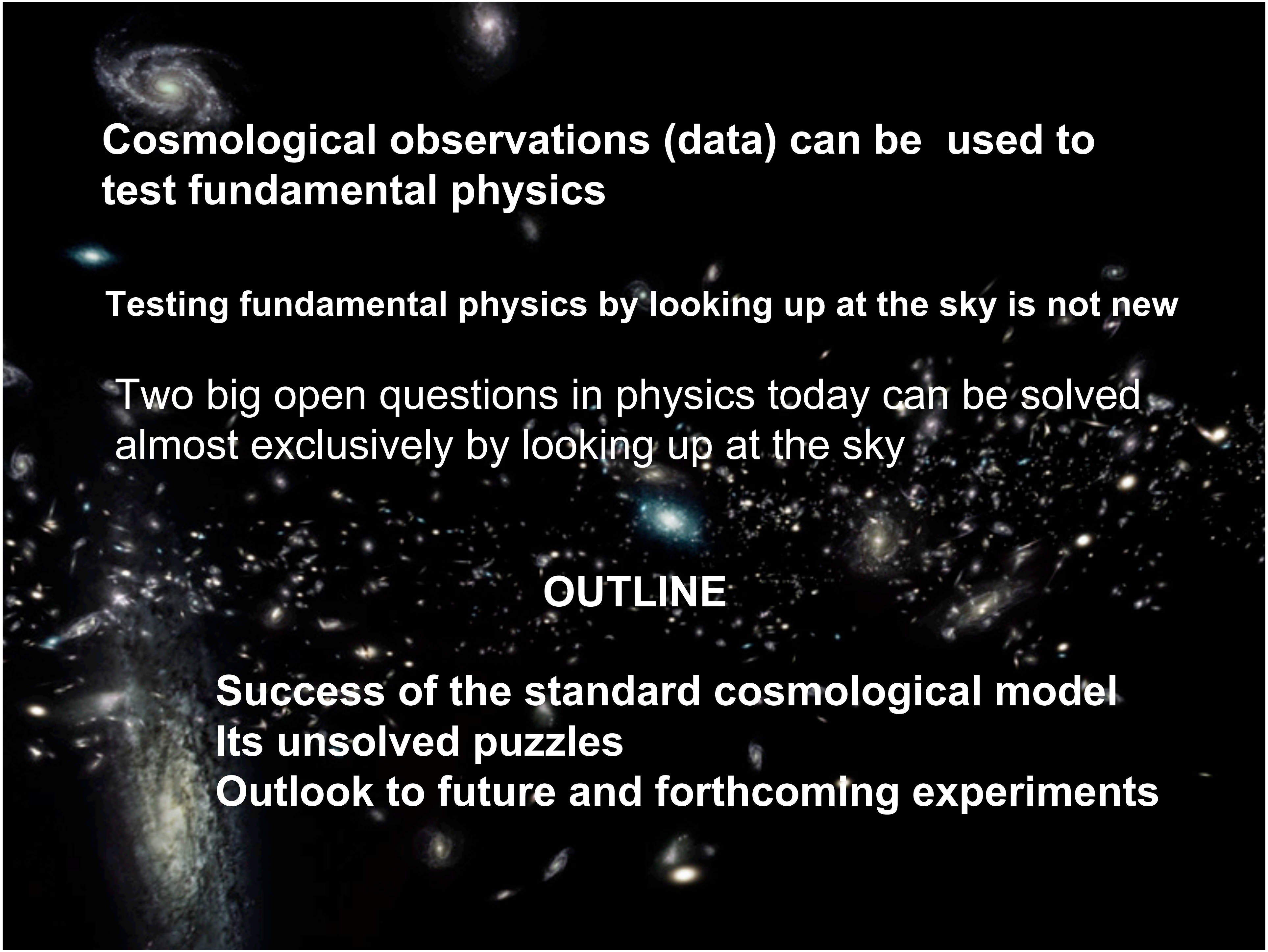
Why should you care about observational cosmology?



Licia Verde

University of Pennsylvania
Princeton University

www.physics.upenn.edu/~lverde

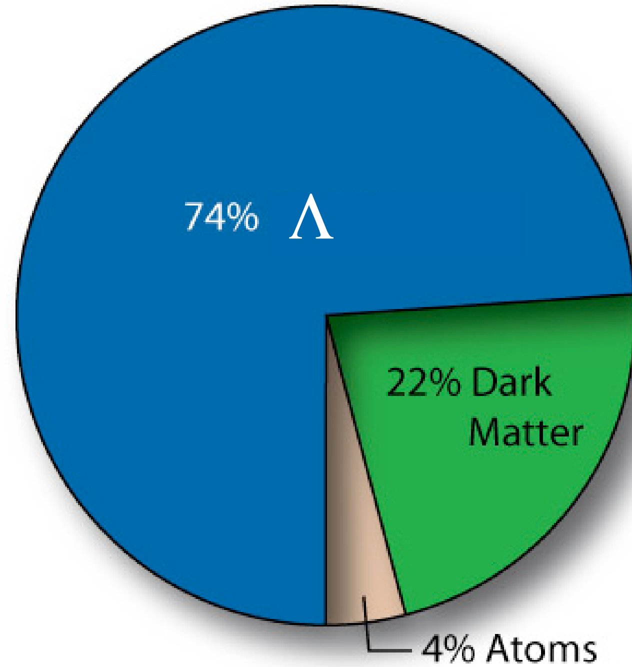

Cosmological observations (data) can be used to test fundamental physics
Testing fundamental physics by looking up at the sky is not new
Two big open questions in physics today can be solved almost exclusively by looking up at the sky
OUTLINE
Success of the standard cosmological model
Its unsolved puzzles
Outlook to future and forthcoming experiments

The standard cosmological model

ΛCDM model

Spatially flat Universe

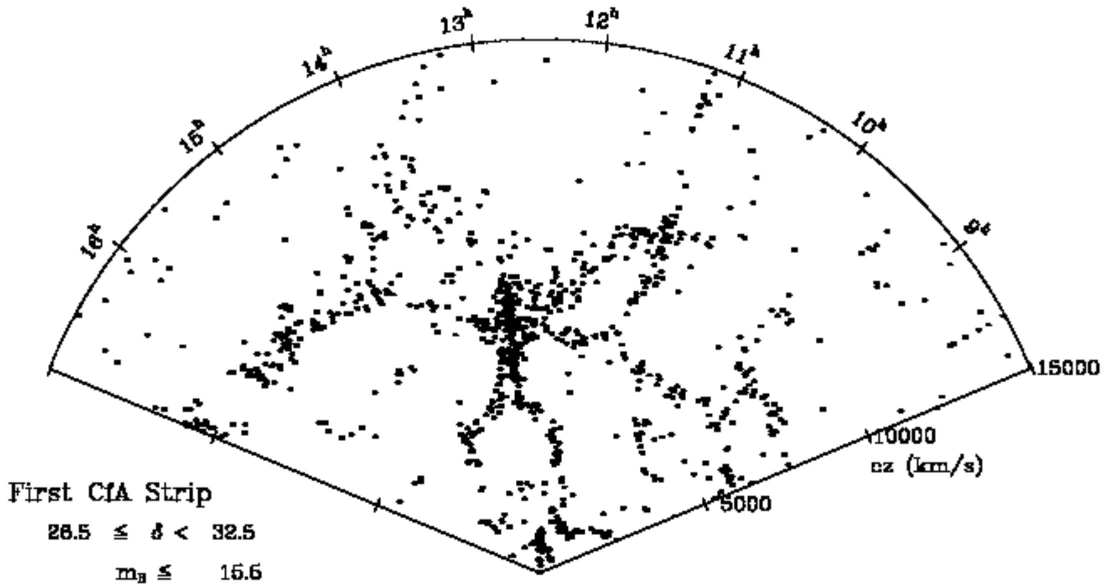
Power-law, primordial power spectrum

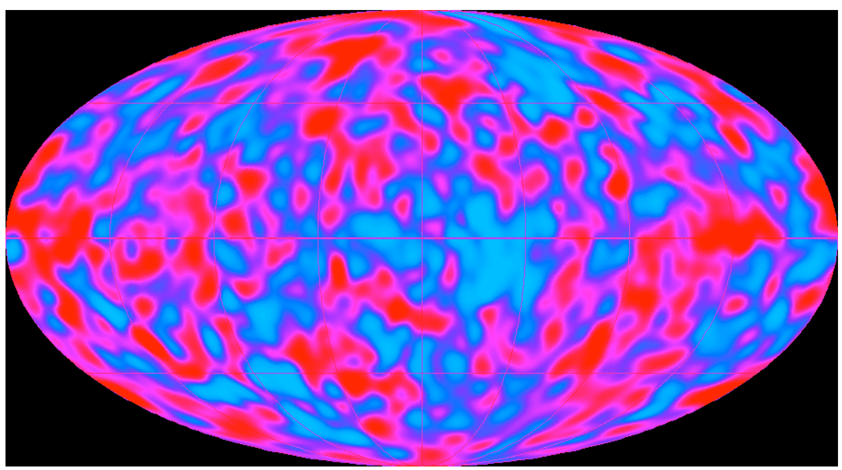


Only 6 parameters

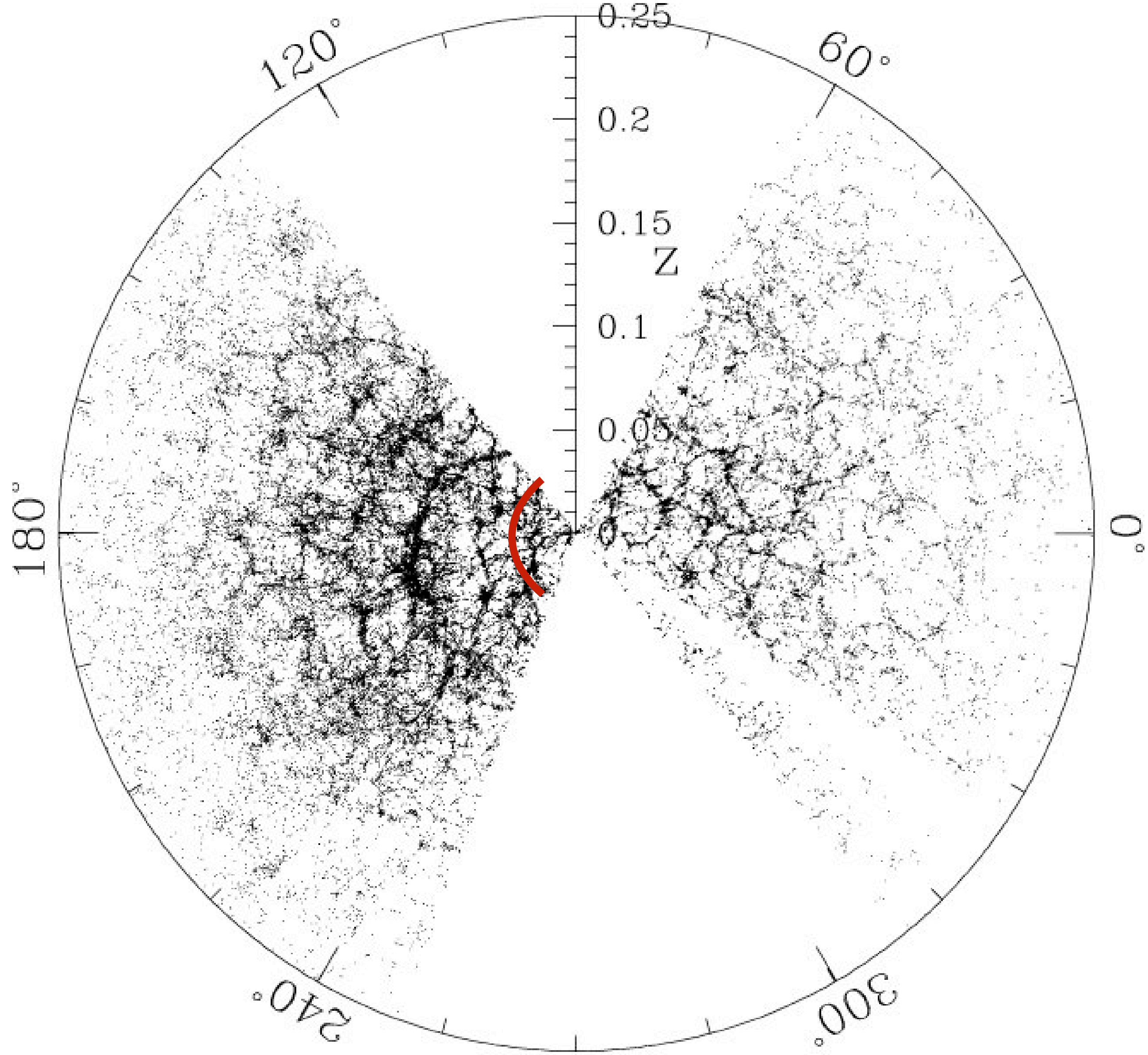
Parameter	WMAP Only	WMAP +CBI+VSA	WMAP+ACBAR +BOOMERanG	WMAP + 2dFGRS	WMAP+ SDSS	WMAP+ SNLS	WMAP + SN Gold
$100\Omega_b h^2$	$2.233^{+0.072}_{-0.091}$	$2.212^{+0.066}_{-0.084}$	$2.231^{+0.070}_{-0.088}$	$2.223^{+0.066}_{-0.083}$	$2.233^{+0.062}_{-0.086}$	$2.233^{+0.069}_{-0.088}$	$2.227^{+0.065}_{-0.082}$
$\Omega_m h^2$	$0.1268^{+0.0072}_{-0.0095}$	$0.1233^{+0.0070}_{-0.0086}$	$0.1259^{+0.0077}_{-0.0095}$	$0.1262^{+0.0045}_{-0.0062}$	$0.1329^{+0.0056}_{-0.0075}$	$0.1295^{+0.0056}_{-0.0072}$	$0.1349^{+0.0056}_{-0.0071}$
h	$0.734^{+0.028}_{-0.038}$	$0.743^{+0.027}_{-0.037}$	$0.739^{+0.028}_{-0.038}$	$0.732^{+0.018}_{-0.025}$	$0.709^{+0.024}_{-0.032}$	$0.723^{+0.021}_{-0.030}$	$0.701^{+0.020}_{-0.026}$
A	$0.801^{+0.043}_{-0.054}$	$0.796^{+0.042}_{-0.052}$	$0.798^{+0.046}_{-0.054}$	$0.799^{+0.042}_{-0.051}$	$0.813^{+0.042}_{-0.052}$	$0.808^{+0.044}_{-0.051}$	$0.827^{+0.045}_{-0.053}$
τ	$0.088^{+0.028}_{-0.034}$	$0.088^{+0.027}_{-0.033}$	$0.088^{+0.030}_{-0.033}$	$0.083^{+0.027}_{-0.031}$	$0.079^{+0.029}_{-0.032}$	$0.085^{+0.028}_{-0.032}$	$0.079^{+0.028}_{-0.034}$
n_s	$0.951^{+0.015}_{-0.019}$	$0.947^{+0.014}_{-0.017}$	$0.951^{+0.015}_{-0.020}$	$0.948^{+0.014}_{-0.018}$	$0.948^{+0.015}_{-0.018}$	$0.950^{+0.015}_{-0.019}$	$0.946^{+0.015}_{-0.019}$
σ_8	$0.744^{+0.050}_{-0.060}$	$0.722^{+0.043}_{-0.053}$	$0.739^{+0.047}_{-0.059}$	$0.737^{+0.033}_{-0.045}$	$0.772^{+0.036}_{-0.048}$	$0.758^{+0.038}_{-0.052}$	$0.784^{+0.035}_{-0.049}$
Ω_m	$0.238^{+0.030}_{-0.041}$	$0.226^{+0.026}_{-0.036}$	$0.233^{+0.029}_{-0.041}$	$0.236^{+0.016}_{-0.024}$	$0.266^{+0.026}_{-0.036}$	$0.249^{+0.024}_{-0.031}$	$0.276^{+0.023}_{-0.031}$

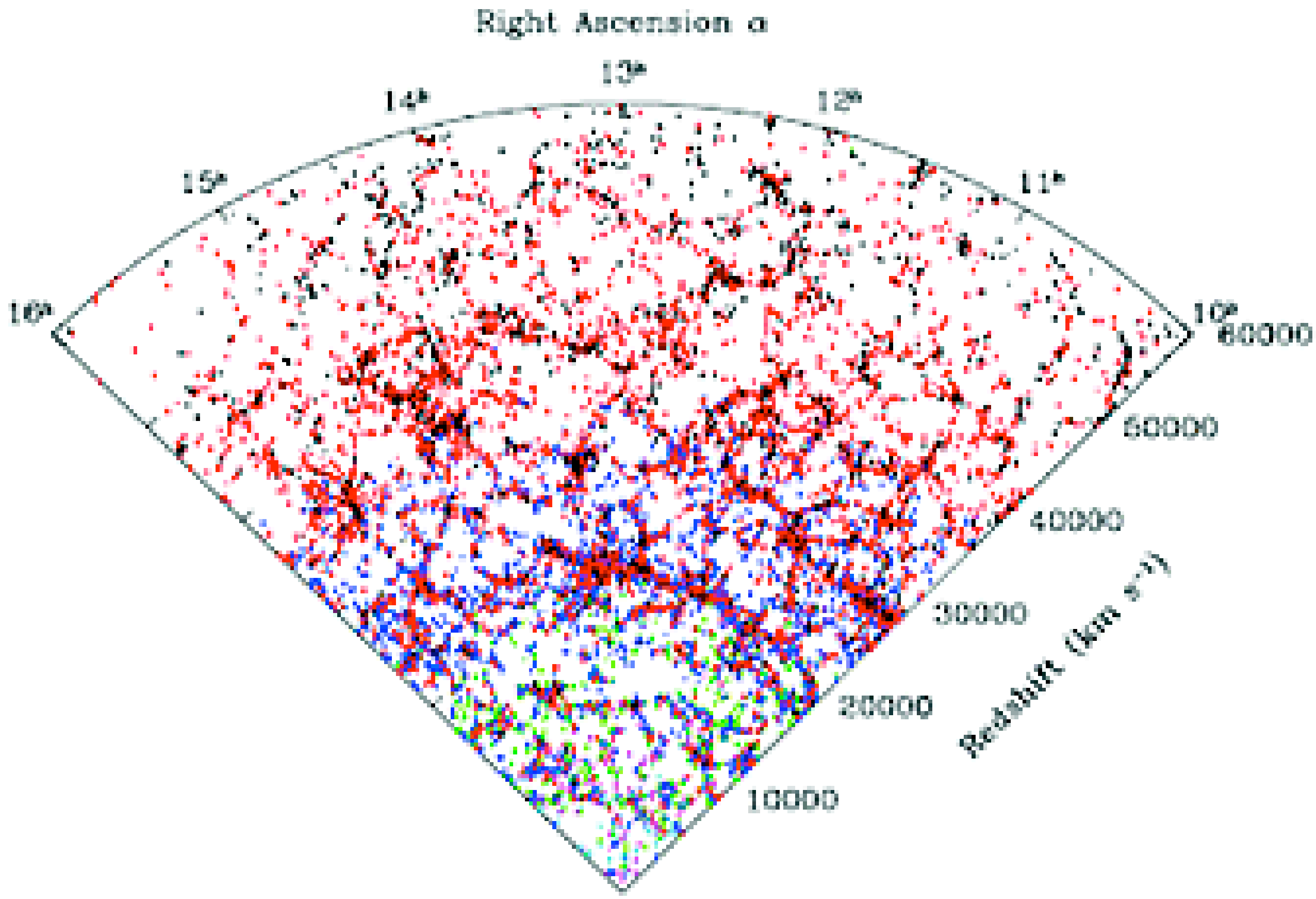
State of the art of data then…





State of the art of data now…

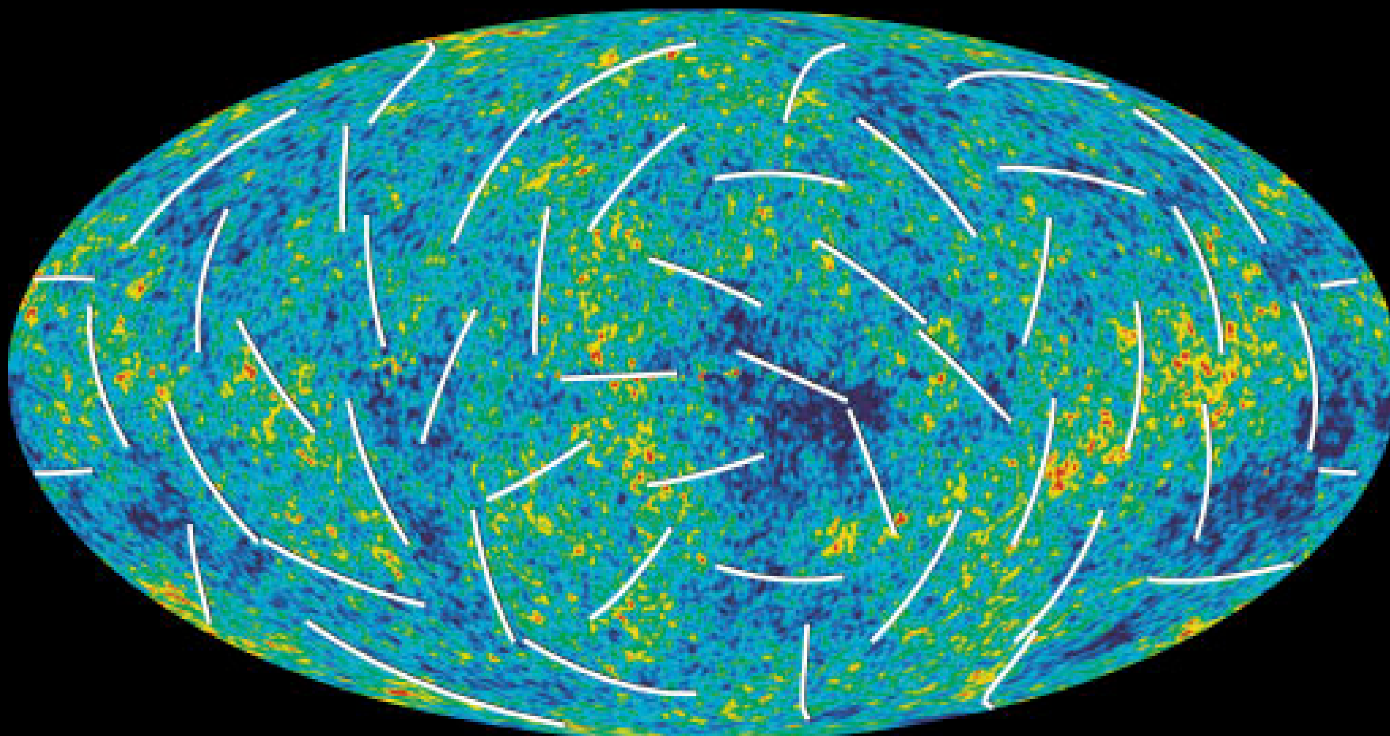




N equatorial slice

Sloan Digital sky survey

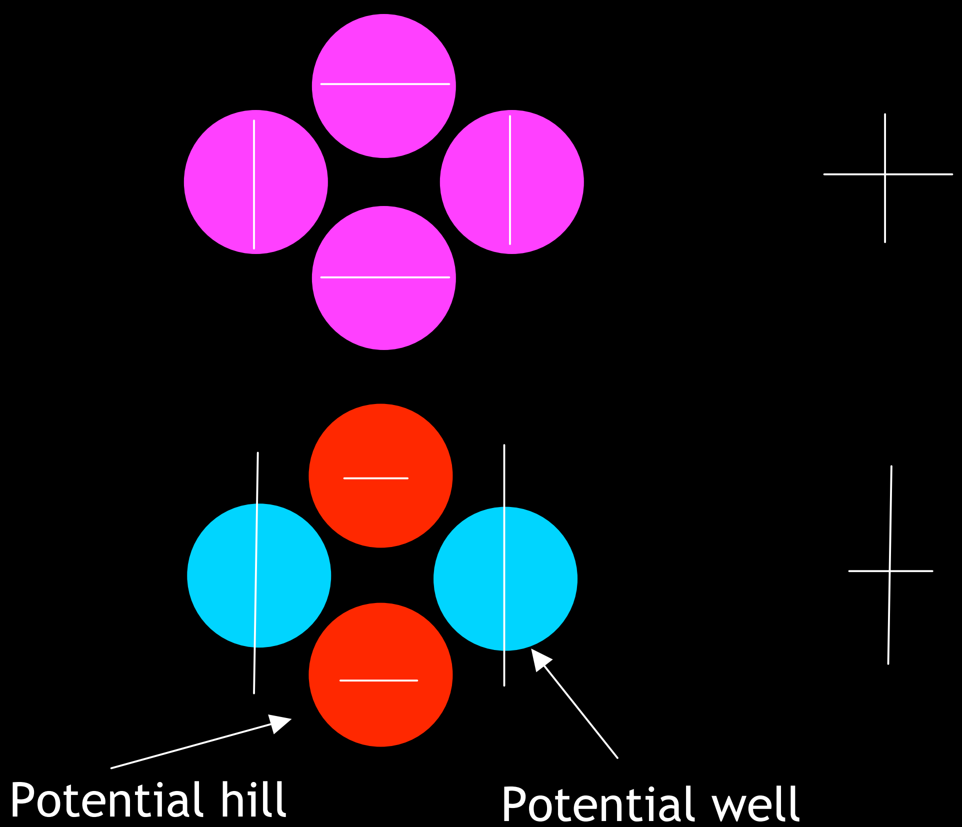
State of the art of data now… (cont'd)

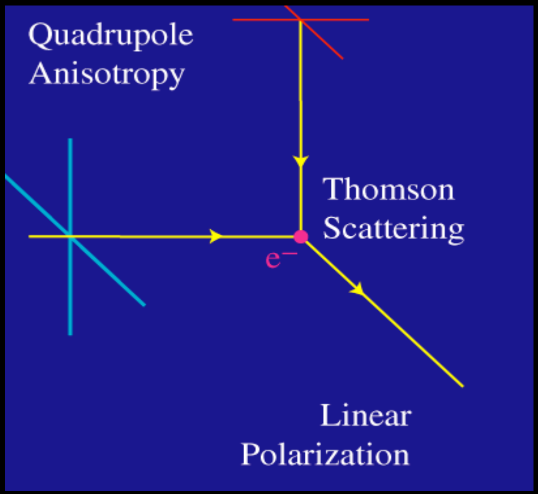


New in 2006

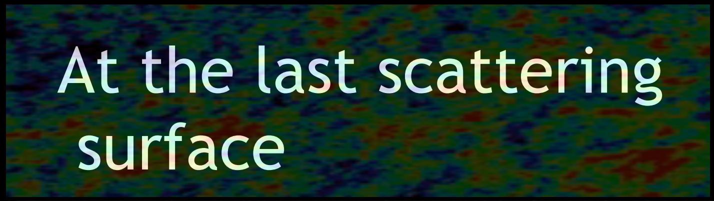
Generation of CMB polarization

- Temperature quadrupole at the surface of last scatter generates polarization.



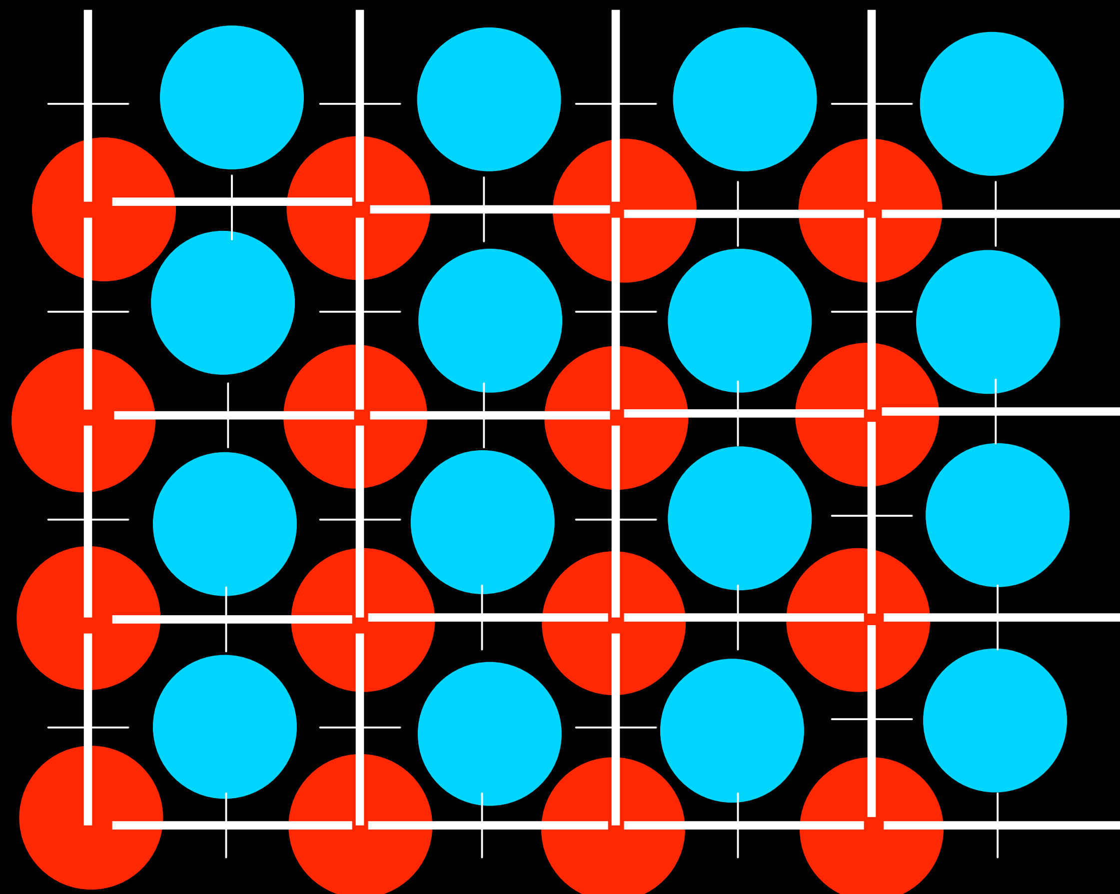


From Wayne Hu



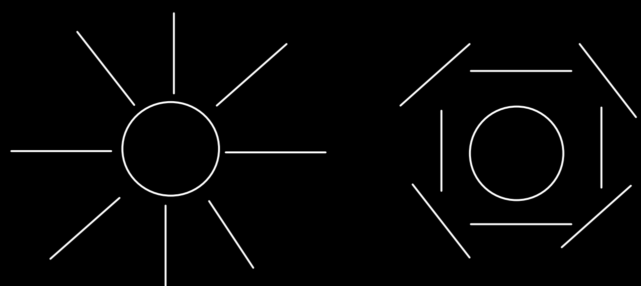
Polarization for density perturbation

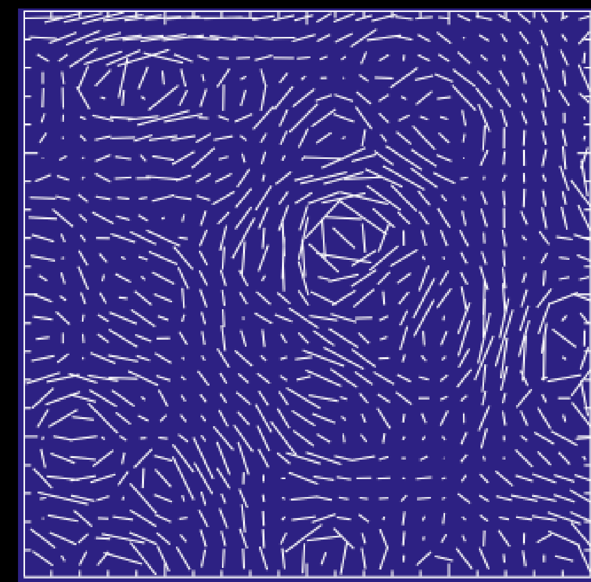
- Radial (tangential) pattern around hot (cold) spots.



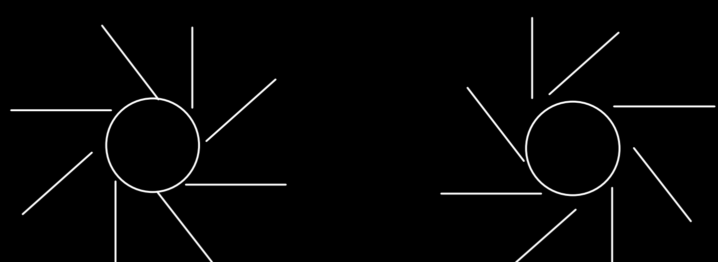
E and B modes polarization

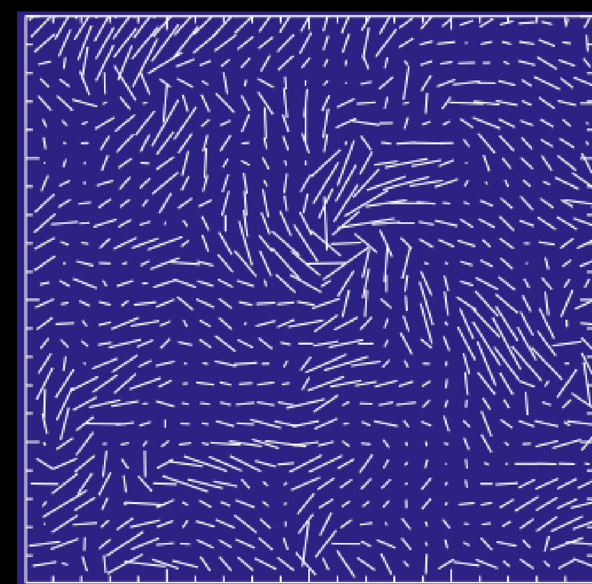
E polarization
from scalar, vector and tensor modes





B polarization only from (vector)
tensor modes (tensor-to scalar ratio r)

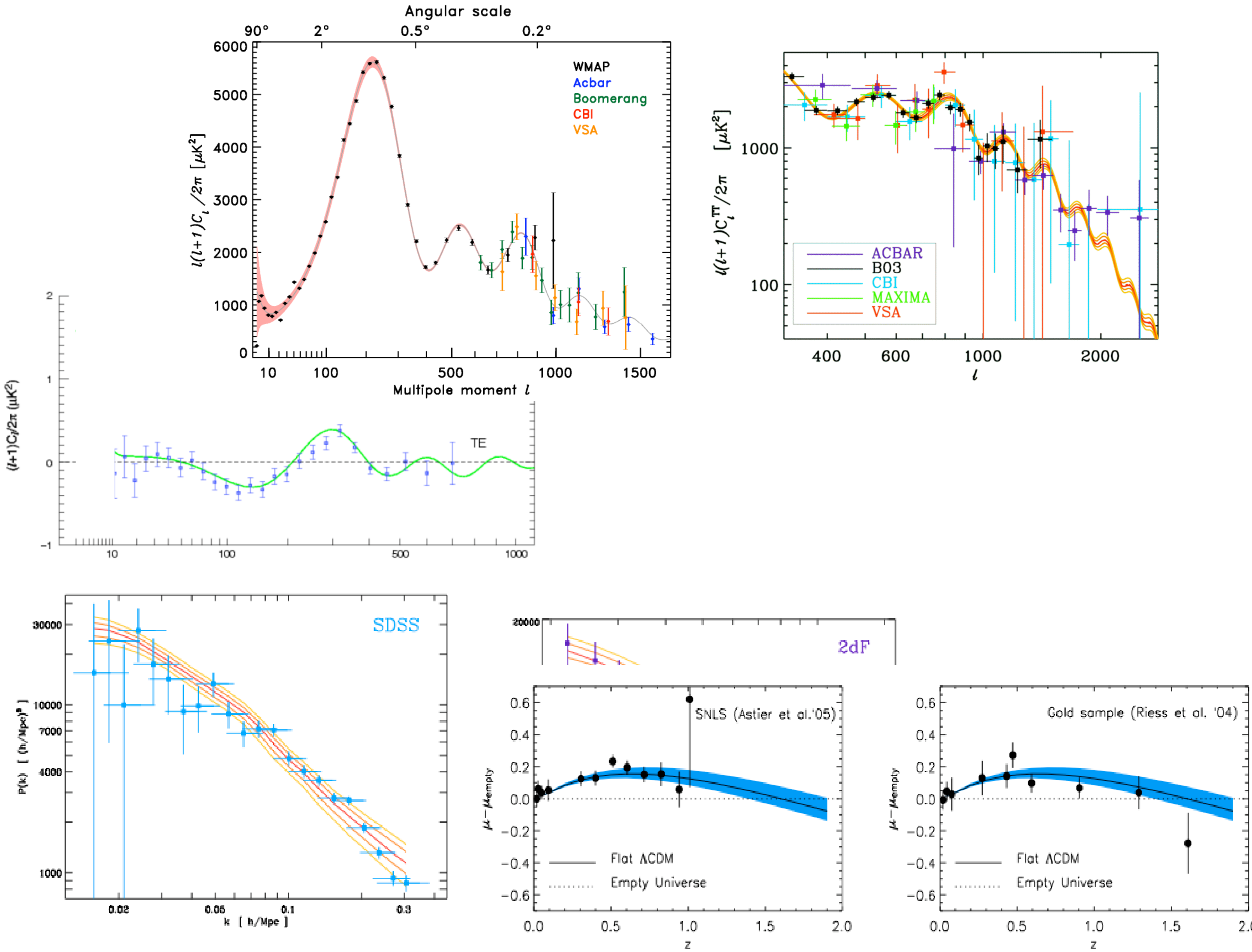




Smoking gun of inflation, holy grail for CMB…

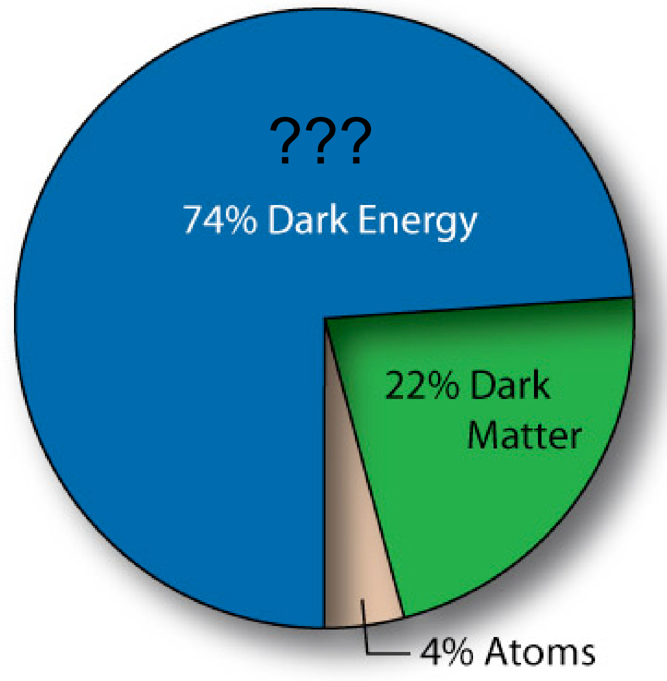
Kamionkowski, Kosowsky, Stebbings 1997, Zaldarriga & Seljak 1997

Success of the standard cosmological model:

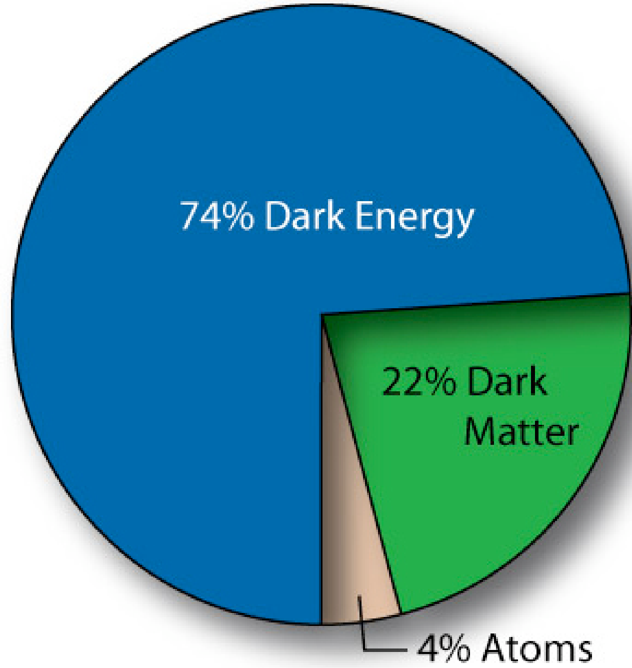


The standard cosmological model

96% of the Universe is missing!!!



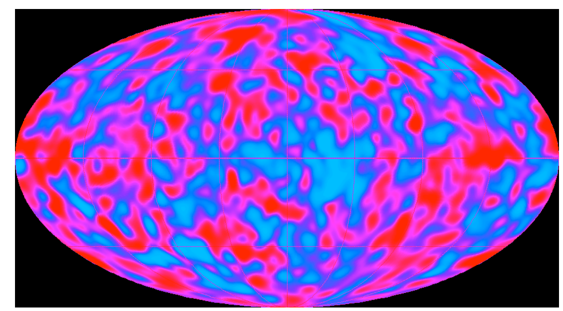
The standard cosmological model



96% of the Universe is missing!!!

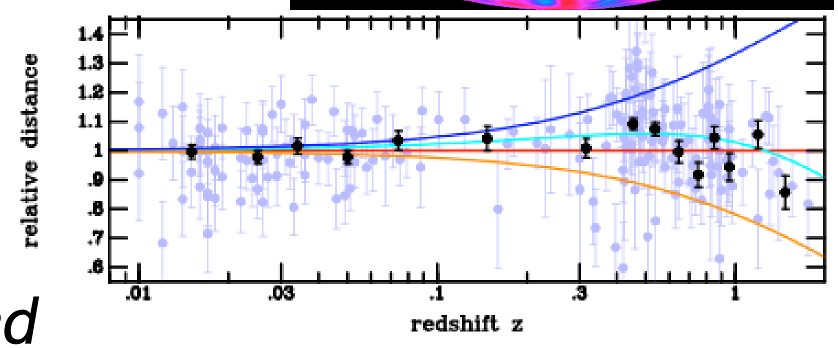
Major questions :

Questions that can be addressed exclusively by looking up at the sky



1)What created the primordial perturbations?

2) What makes the Universe accelerate?



These questions may not be unrelated

Three important documents

(will probably shape observational cosmology for the next 10 years)

"Task force on CMB research" report
(to advise DoE, NSF, NASA):
Bock et al. 2006 (arXiv:astro-ph/0604101)

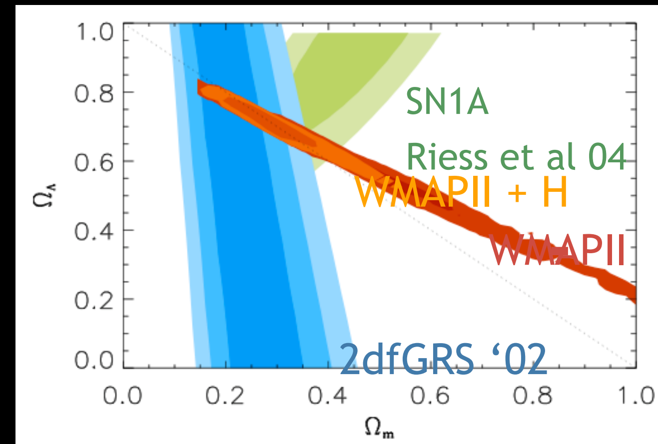
"The dark energy task force report"
(to advise DoE, NSF, NASA):
Albrecht et al. 2006 (arXiv:astro-ph/0609591)

"The report by the ESA-ESO Working Group on Fundamental Cosmology"
Peacock et al 2006 (astro-ph/0610906)

Origins of primordial fluctuations: Clues

- Flat universe:

	Ω_K
WMAP + $h = 0.72 \pm 0.08$	-0.014 ± 0.017
WMAP + SDSS	$-0.0053^{+0.0068}_{-0.0060}$
WMAP + 2dFGRS	$-0.0093^{+0.0098}_{-0.0092}$
WMAP + SDSS LRG	-0.012 ± 0.010
WMAP + SNLS	-0.011 ± 0.012
WMAP + SNGold	-0.023 ± 0.014



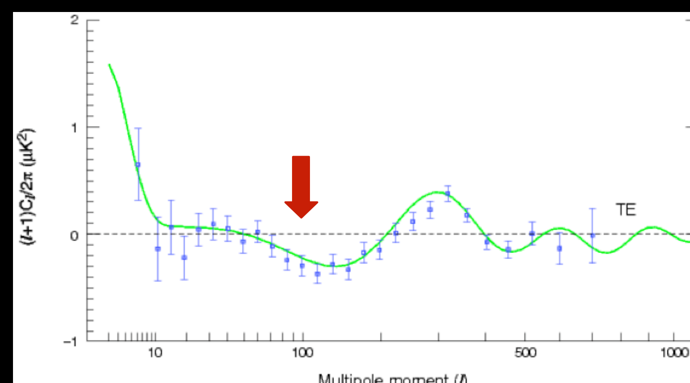
- Gaussianity: $-54 < f_{NL} < 114$

- Power Spectrum spectral index nearly scale-invariant:

n_s	WMAP	WMAP+CMB	WMAP+LSS
	$0.951^{+0.015}_{-0.019}$	$0.947^{+0.014}_{-0.017}$	$0.948^{+0.014}_{-0.018}$

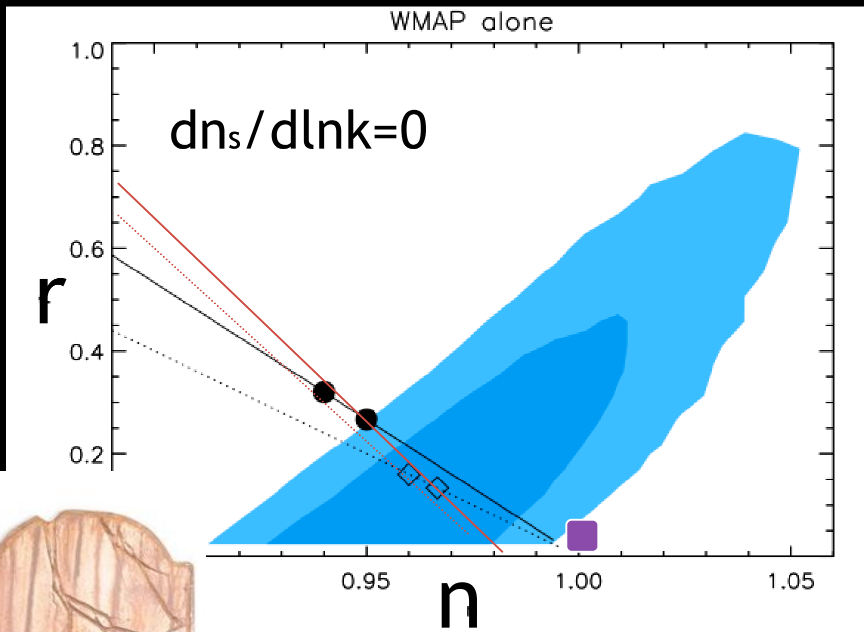
- Adiabatic initial conditions

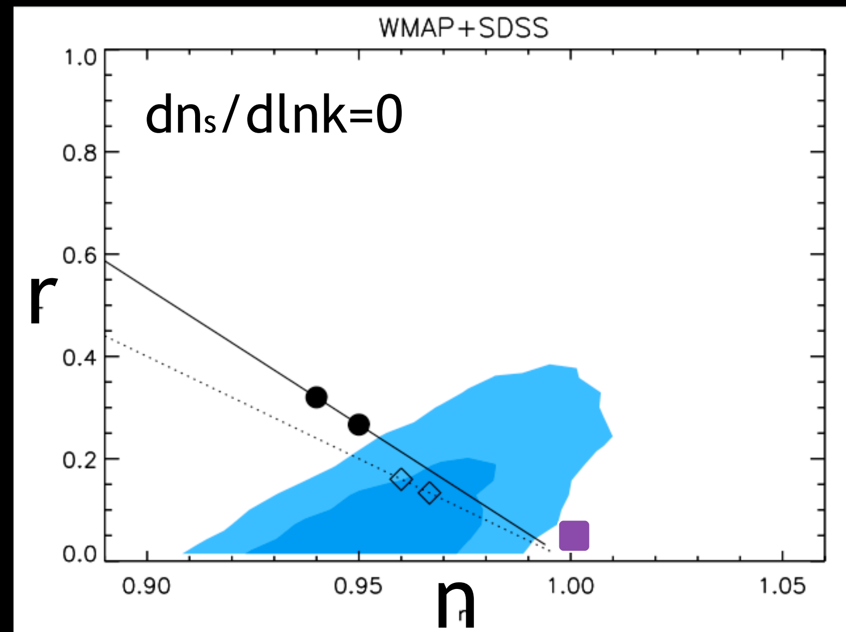
- Superhorizon fluctuations (TE anticorrelations)



Observations Consistent with Simplest Inflationary Models

Specific models critically tested





Models like $V(\phi) \sim \phi^p$

○ p=4 ◆ p=2 For 50 and 60 e-foldings

■ HZ

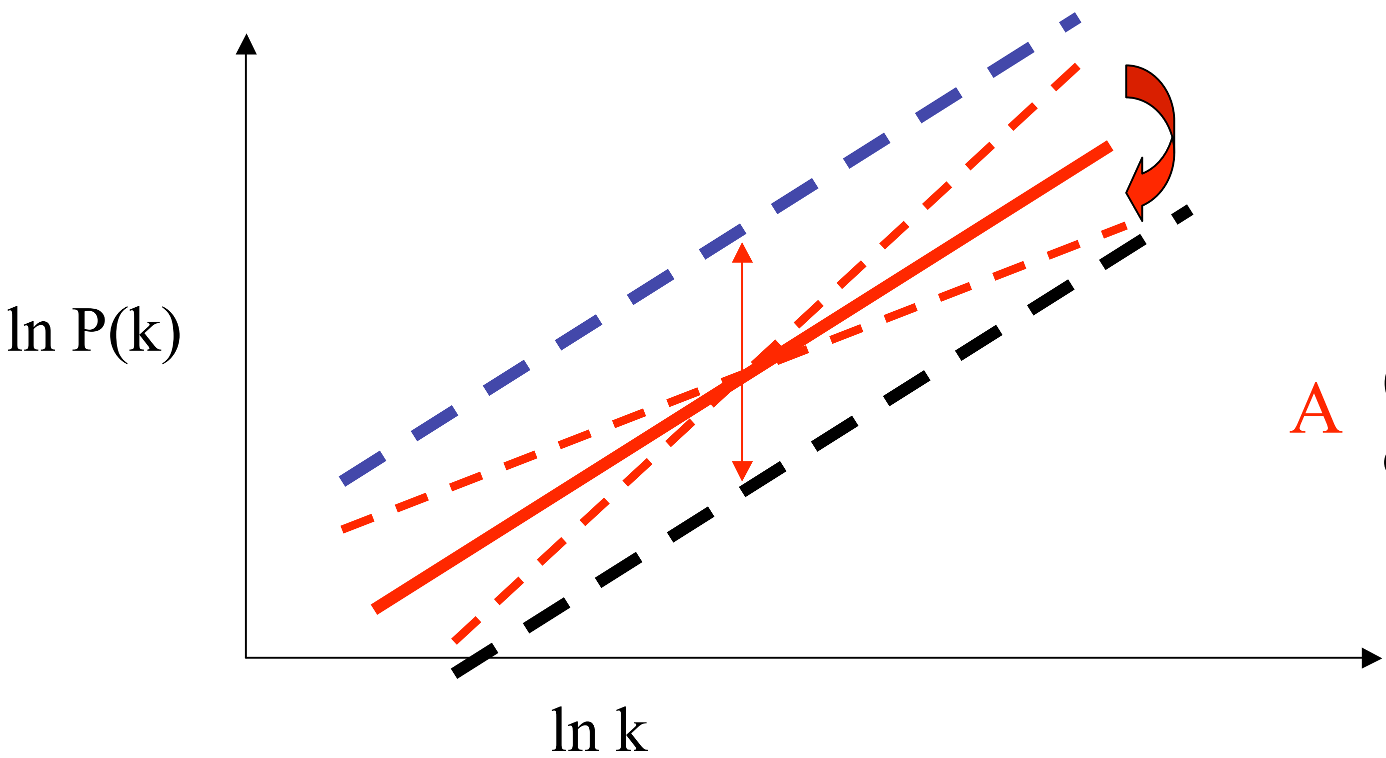
p fix, Ne varies

p varies, Ne fix

Primordial power spectrum= $A\ k^{n}$

Amplitude of the power law

slope

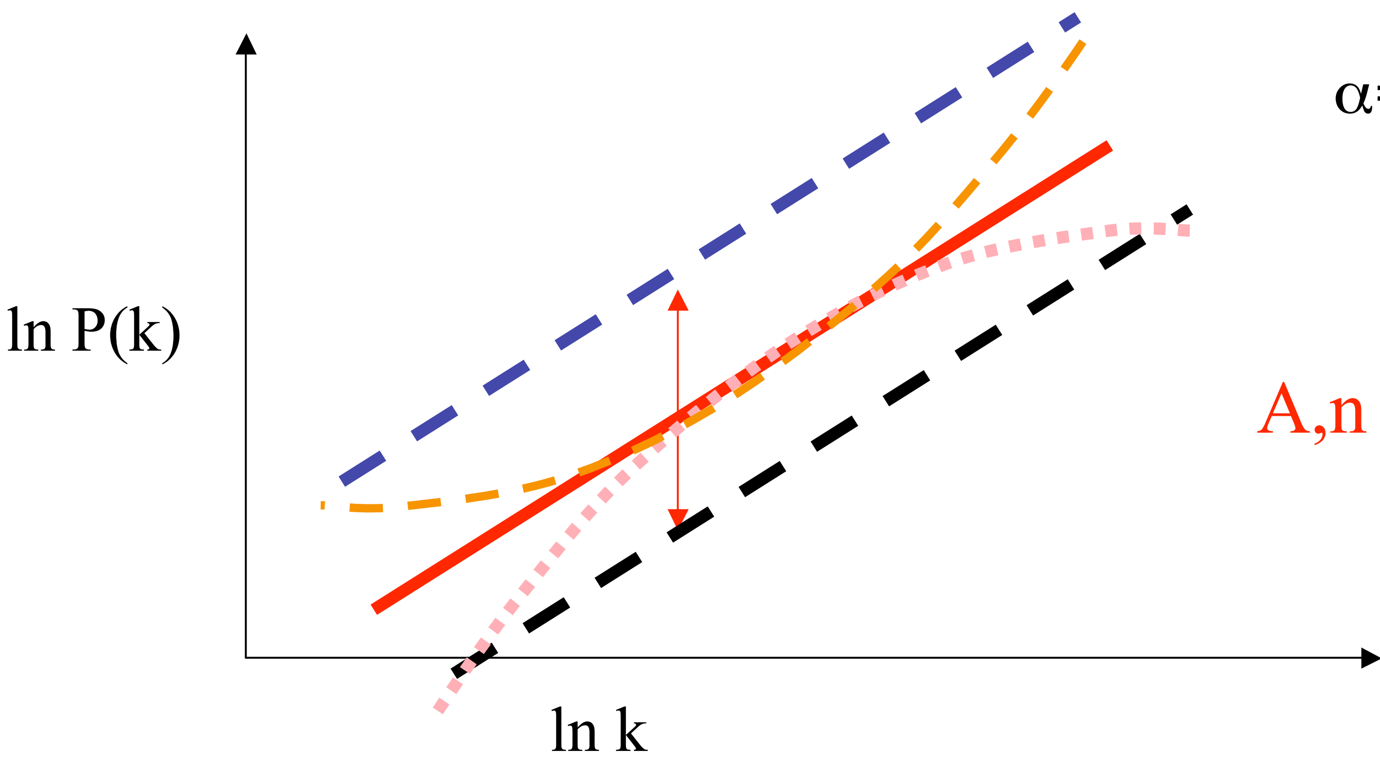


A (convention dependent)

Primordial power spectrum= A $k^{n(k)}$

Amplitude of the power law

slope

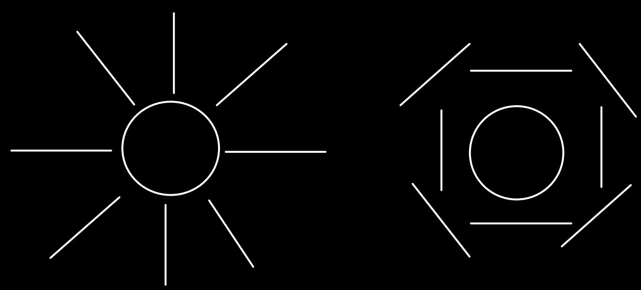


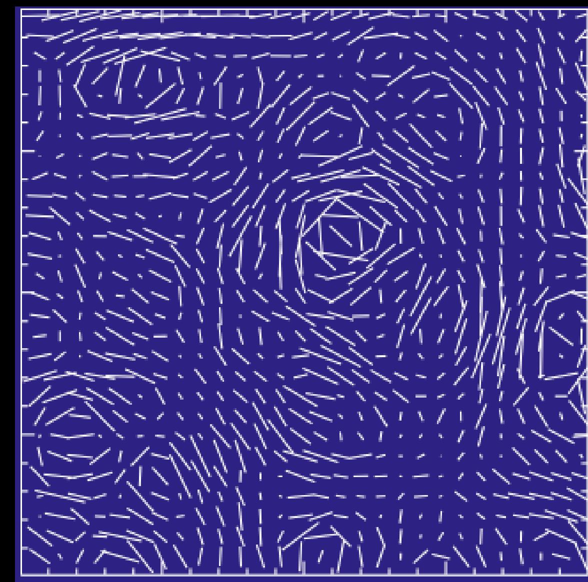
α=dn/dlnk

A,n (convention dependent)

E and B modes polarization

E polarization
from scalar, vector and tensor modes





B polarization only from (vector)
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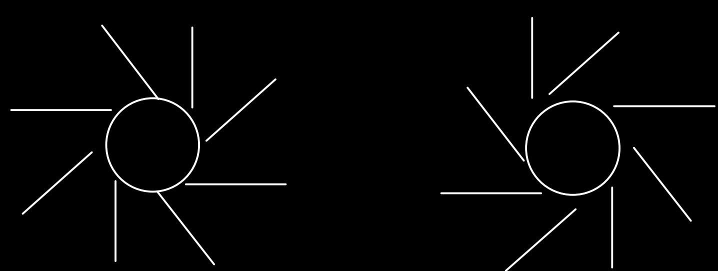
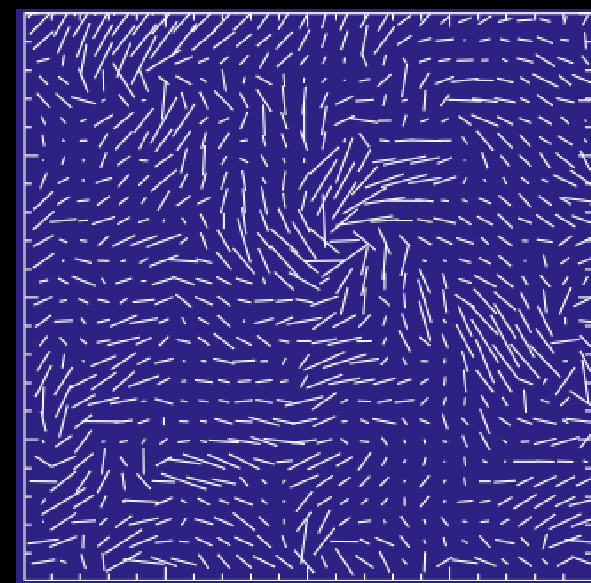




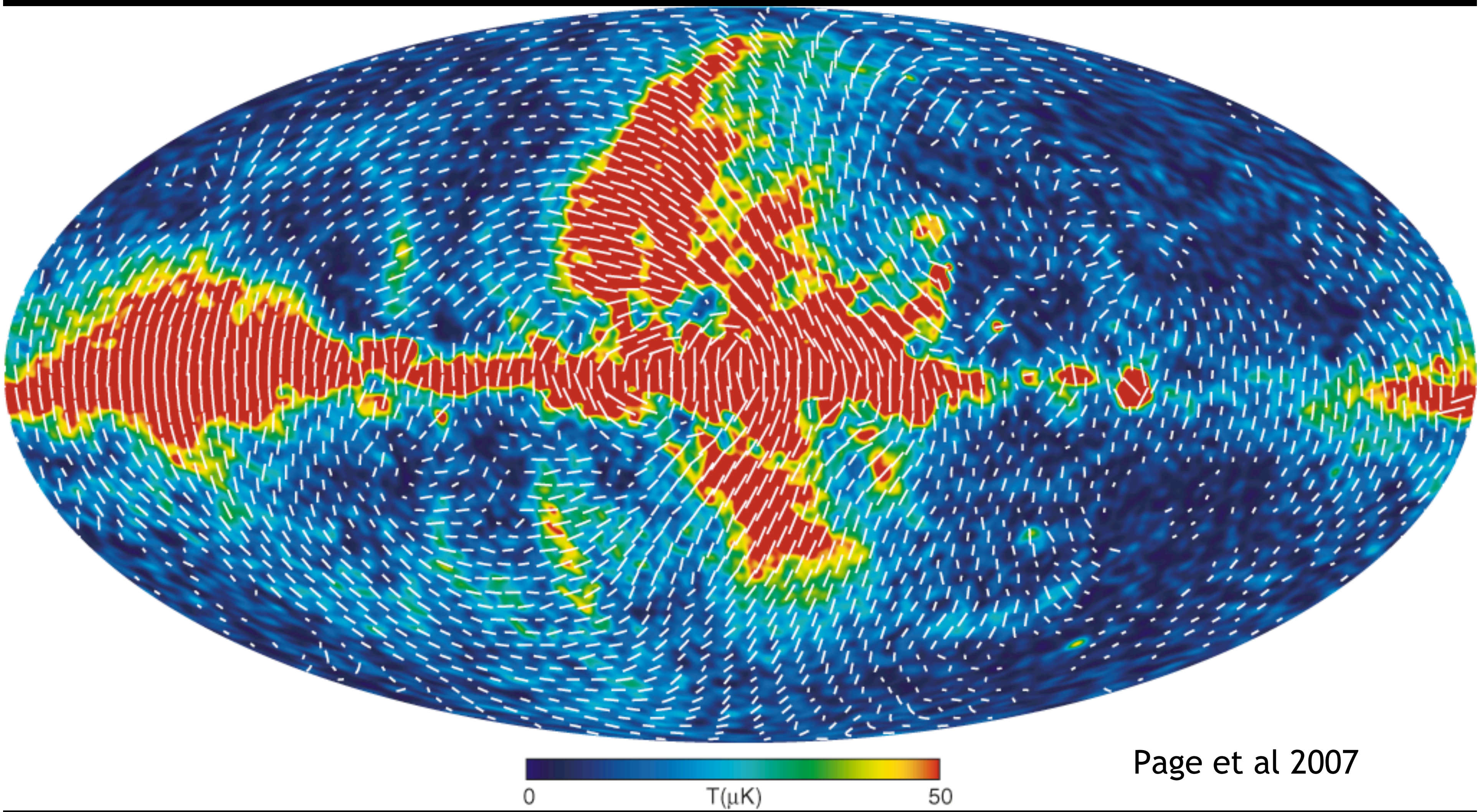
Smoking gun of inflation, holy grail for CMB…

Kamionkowski, Kosowsky, Stebbings 1997, Zaldarriga & Seljak 1997

We happen to live in a galaxy!

K Band (23 GHz)

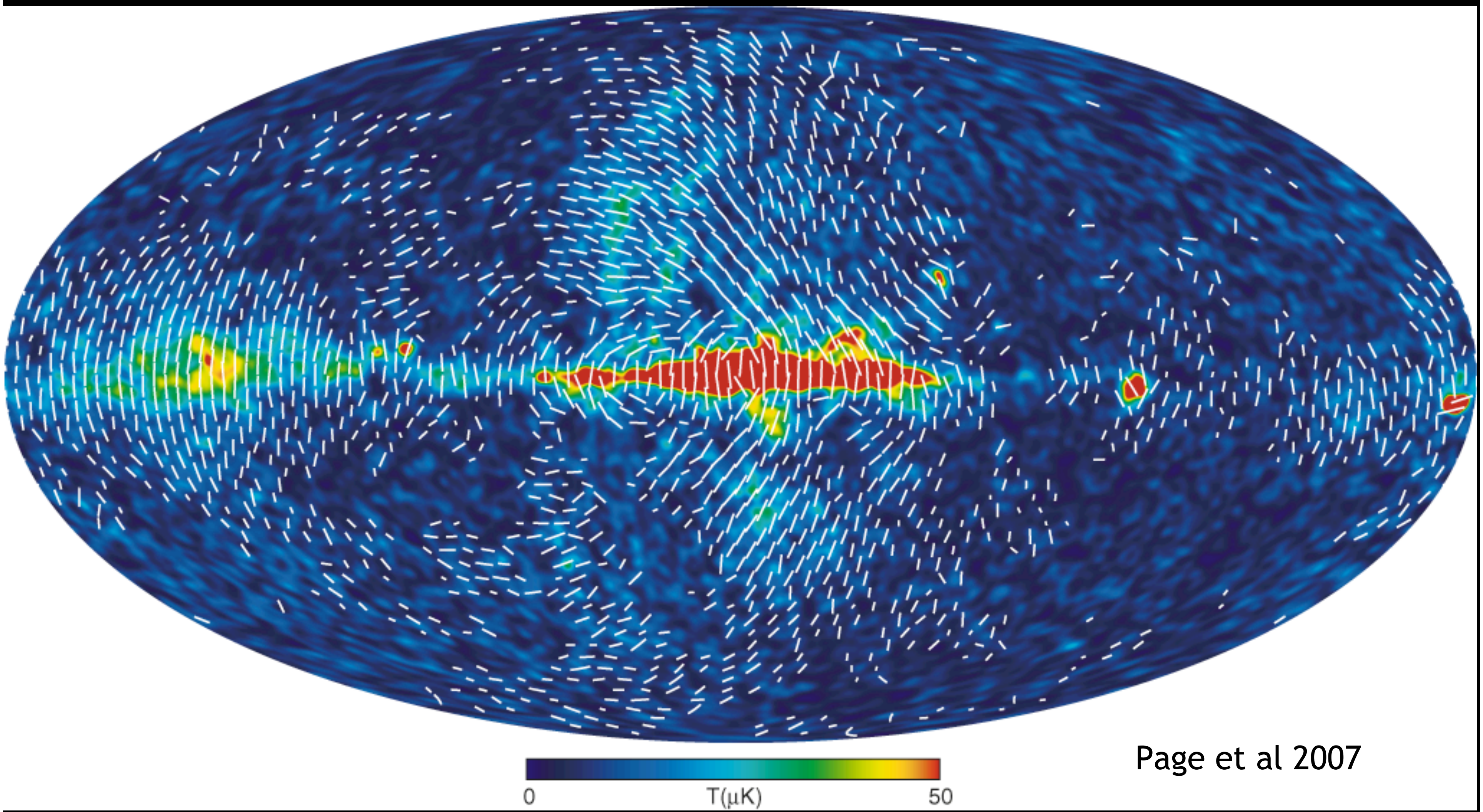
Dominated by synchrotron; Note that polarization direction is perpendicular to the magnetic field lines.



Page et al 2007

Ka Band (33 GHz)

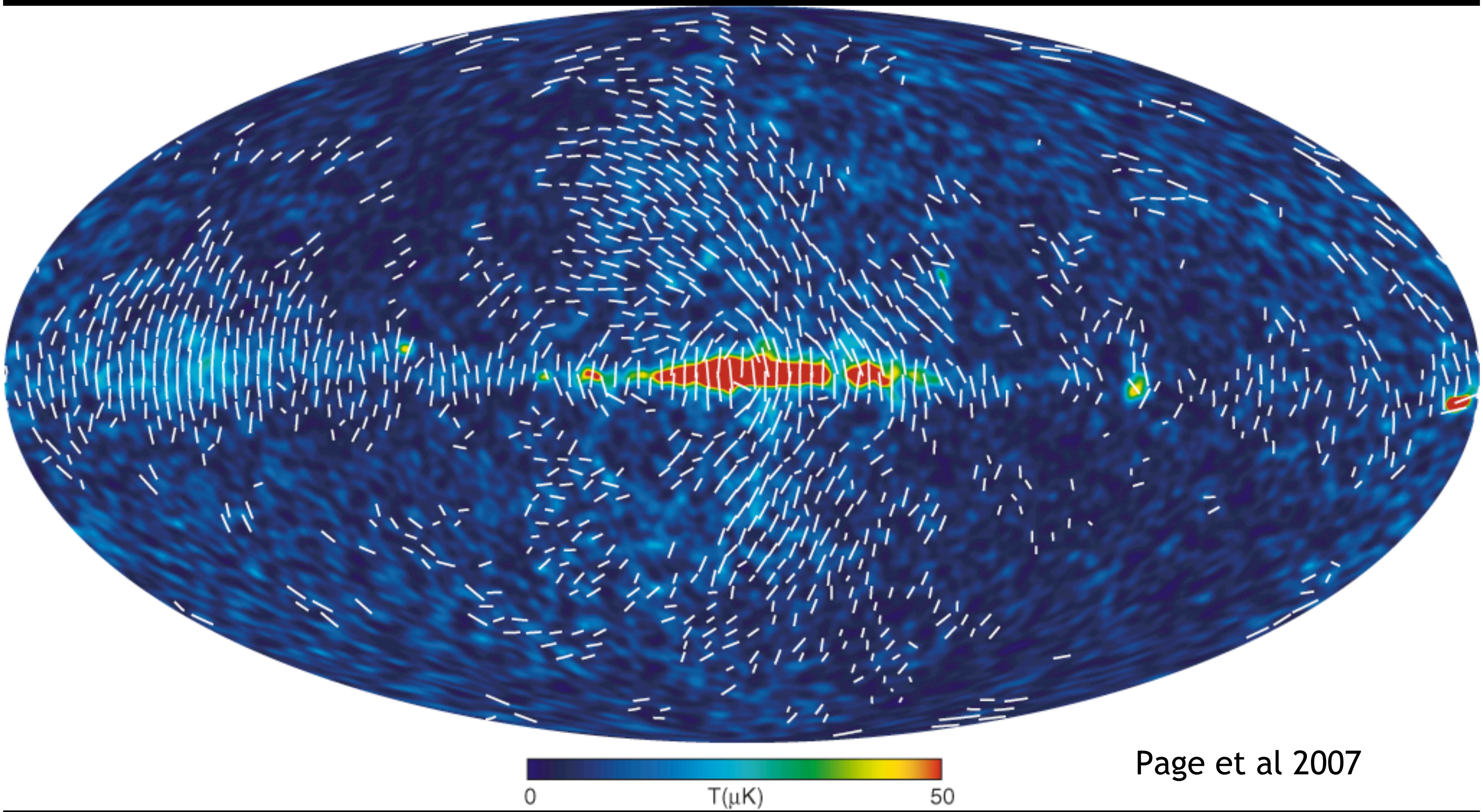
Synchrotron decreases as $n^{-3.2}$ from K to Ka band.



Page et al 2007

Q Band (41 GHz)

We still see significant polarized synchrotron in Q.



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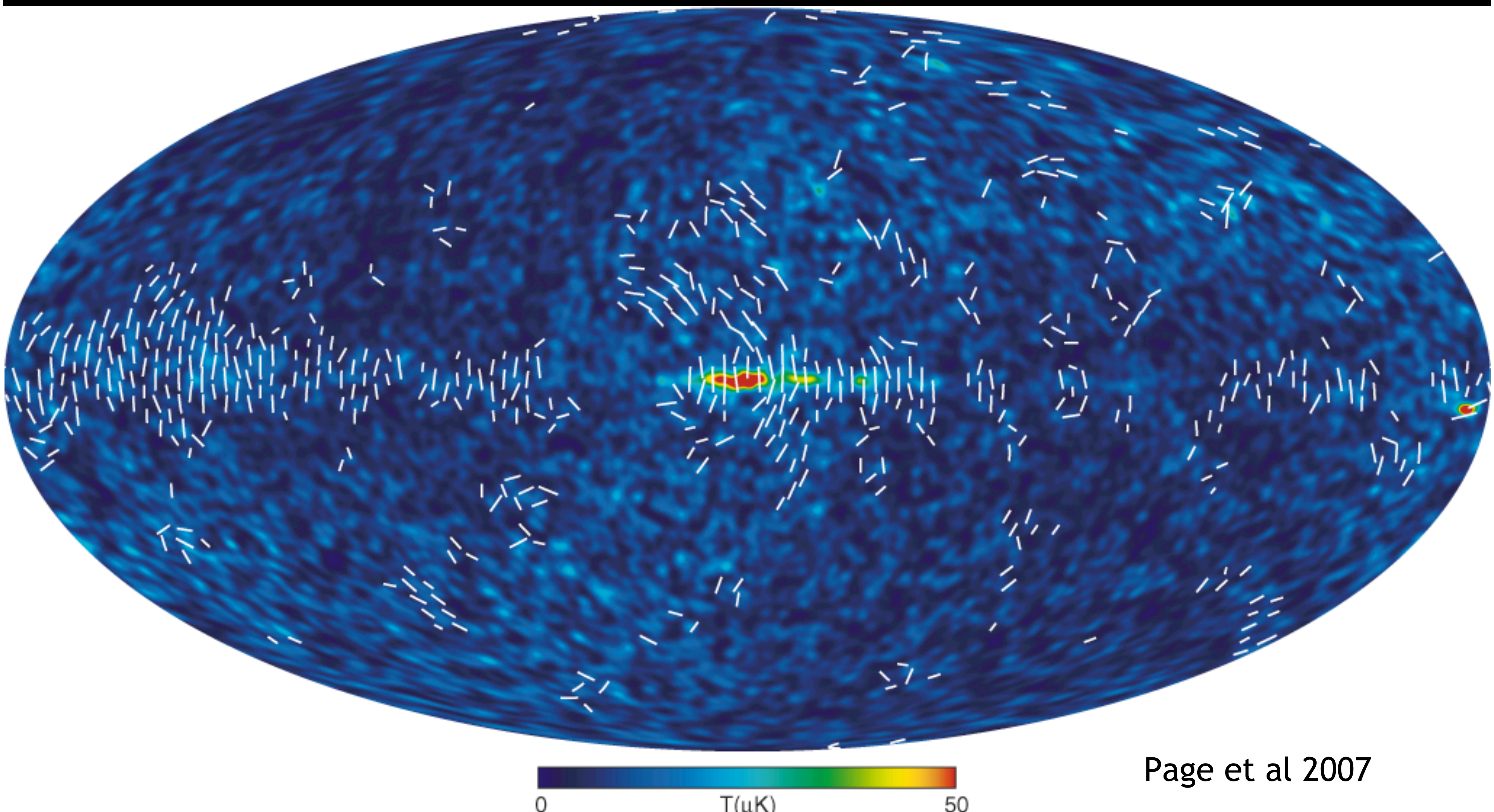
V Band (61 GHz)

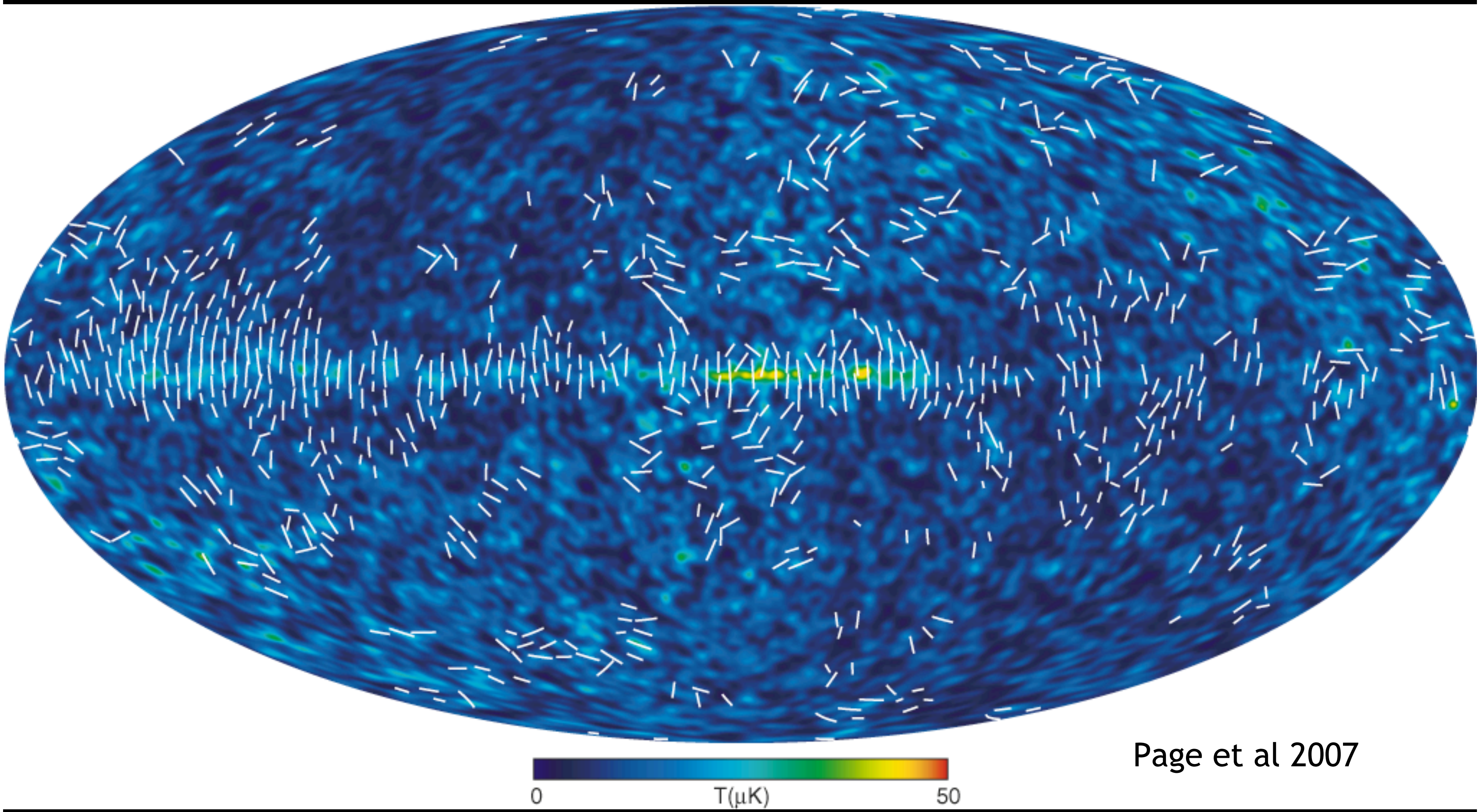
The polarized foreground emission is also smallest in V band.
We can also see that noise is larger on the ecliptic plane.



Page et al 2007

W Band (94 GHz)

While synchrotron is the smallest in W, polarized dust (hard to see by eye) may contaminate in W band more than in V band.



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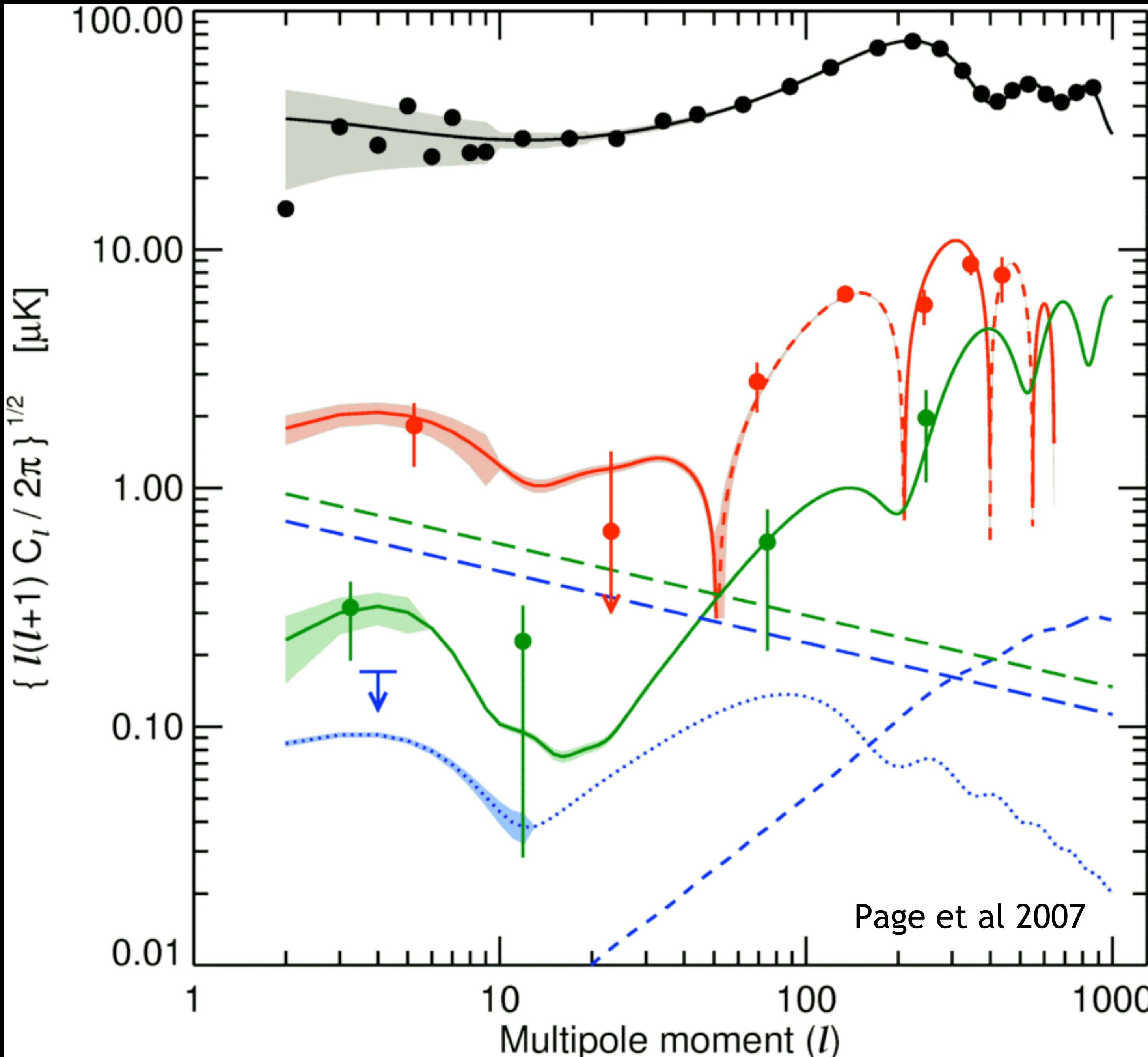
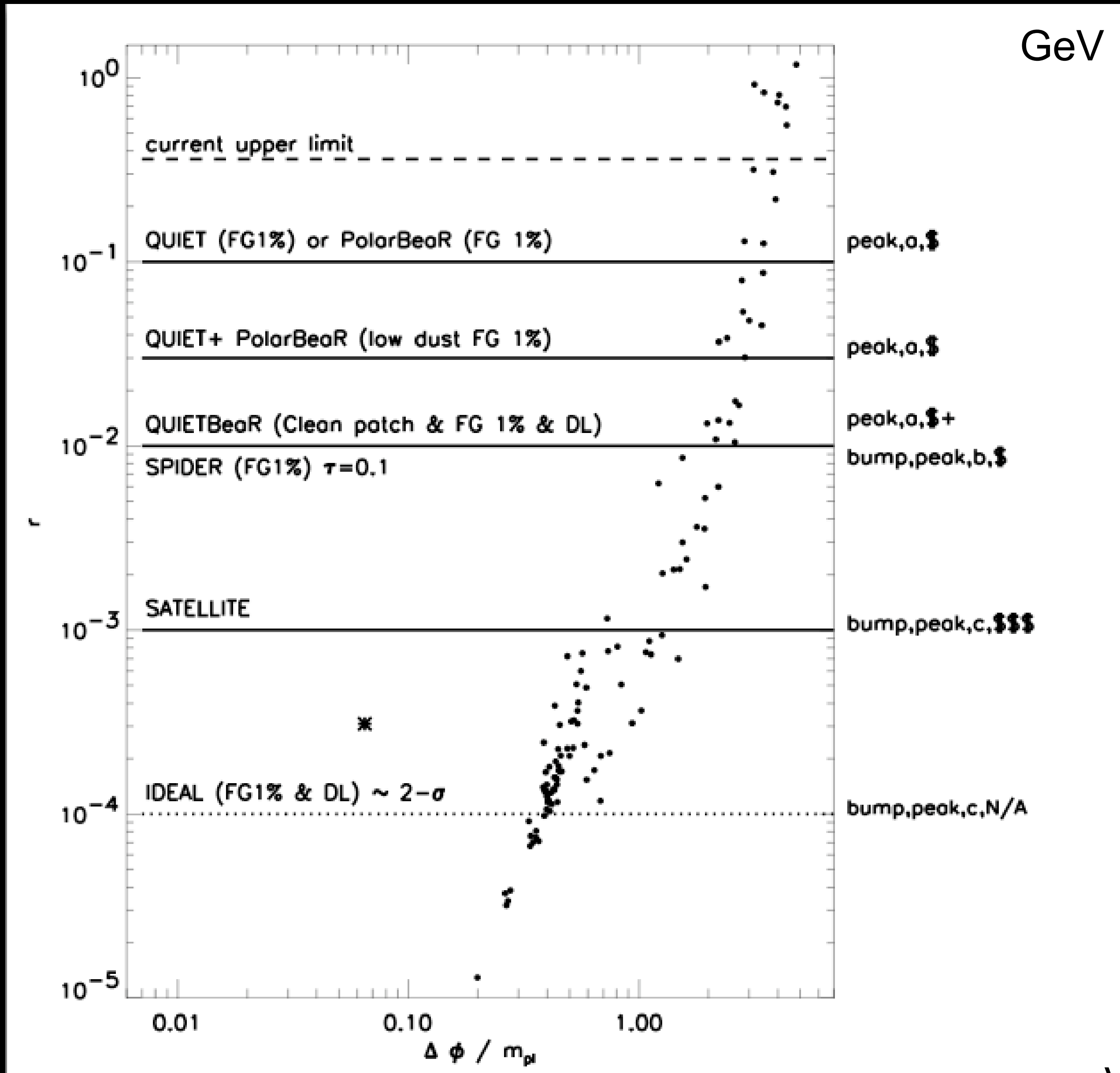


100.00
10.00
1.00
0.10
0.01
1
10
100
1000
Multipole moment (l)
{ l(l+1) C_l / 2π }^1/2 [μK]
Page et al 2007

The next frontier: gravity waves



$3.2\text{x}10^{16}$

$1.7\text{x}10^{16}$

$9.7\text{x}10^{15}$

$5.5\text{x}10^{15}$

$3\text{x}10^{15}$

DARK ENERGY

THE SYMPTOMS

Or OBSERVATIONAL EFFECTS of DARK ENERGY

Recession velocity vs brightness of standard candles: dL(z)

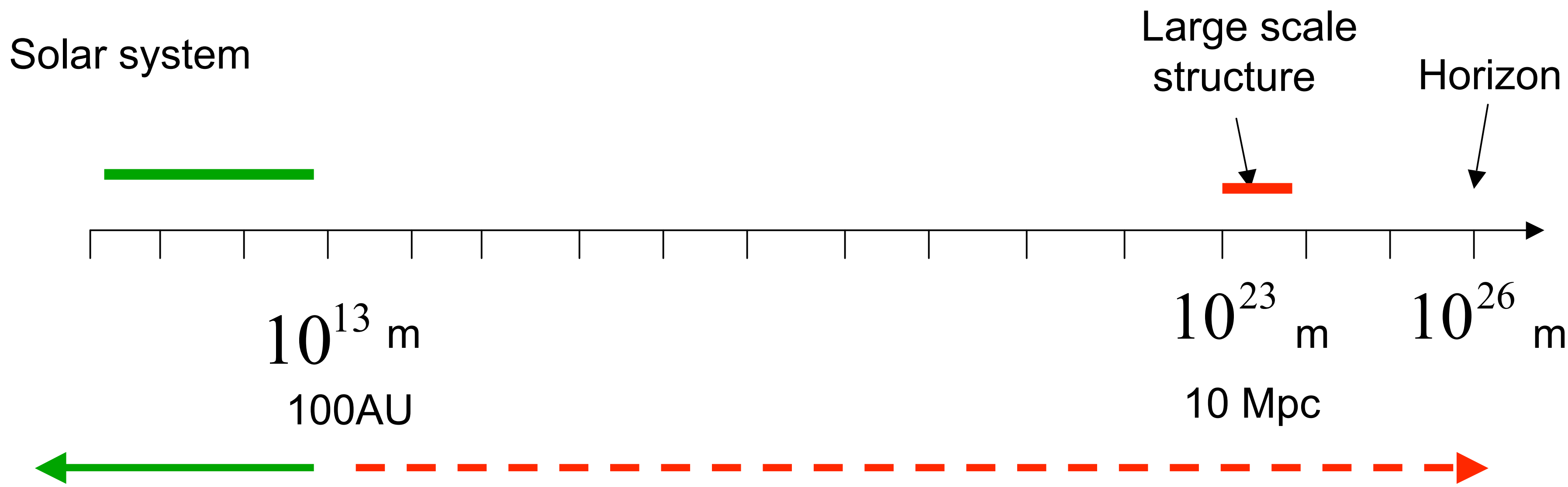
CMB acoustic peaks: Da to last scattering

LSS:
- Da to z_{survey}
- perturbations amplitude today, to be compared with CMB
- Perturbation amplitude at z_{survey}

Something on large scales?

Dark energy shows its effects on scales comparable to the horizon… 10^{26} m

Precision test of the law of gravity have been carried out on scales< 10^{13} m



An enormous extrapolation is required

HOW TO MAKE A DIAGNOSIS?

Any modification of gravity of the form of f(R) can be written as a quintessence model for a(t)

This degeneracy is lifted when considering the growth of structure

Effort in determining what the growth of structure is in a given Dark Energy model!

combination of approaches!

Leading observational techniques to go after dark energy

Supernovae (expansion history)

Galaxy clusters number counts (mostly growth of structure)

Weak Lensing (growth of structure and expansion history)

Baryonic Acoustic Oscillations (BAO) (expansion history)

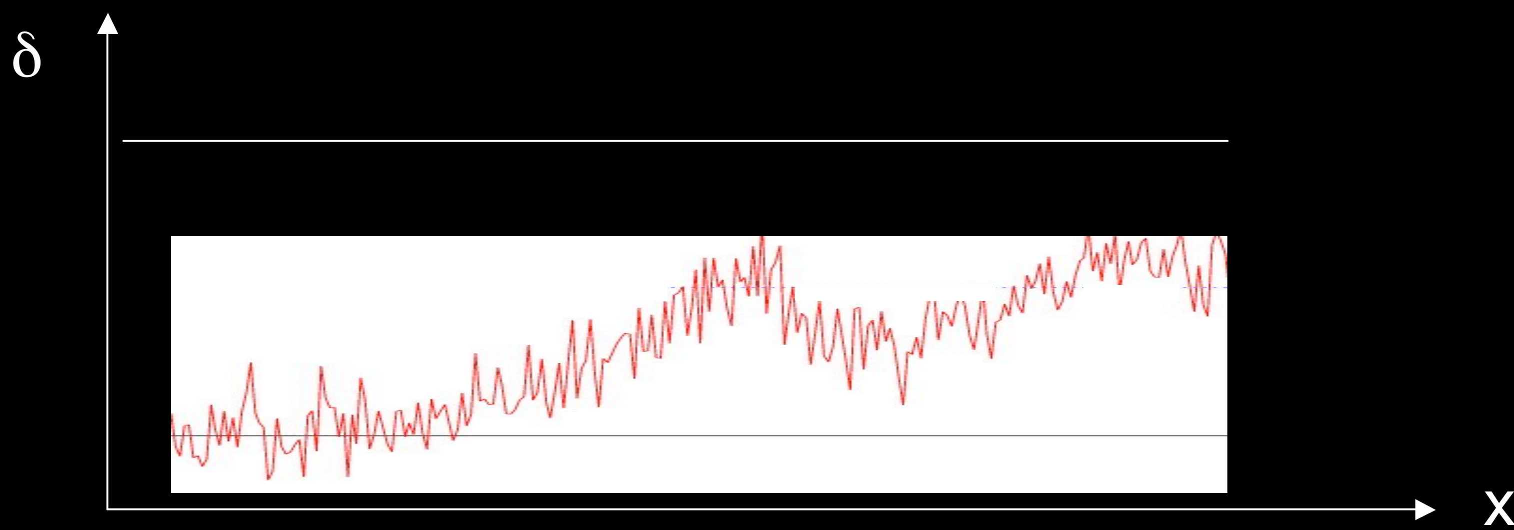
Q: A combination of techniques will be best for at least two reasons

Galaxy clusters number counts

Galaxy clusters are rare events:

$P(M,z) \propto \exp(-\delta^2/\sigma(M,z)^2)$

In here there is the growth of structure



Beware of systematics! “What’s the mass of that cluster?”

Galaxy clusters number counts

Galaxy clusters are rare events:
$P(M,z)$ oc $\exp(-\delta^2/\sigma(M,z)^2)$

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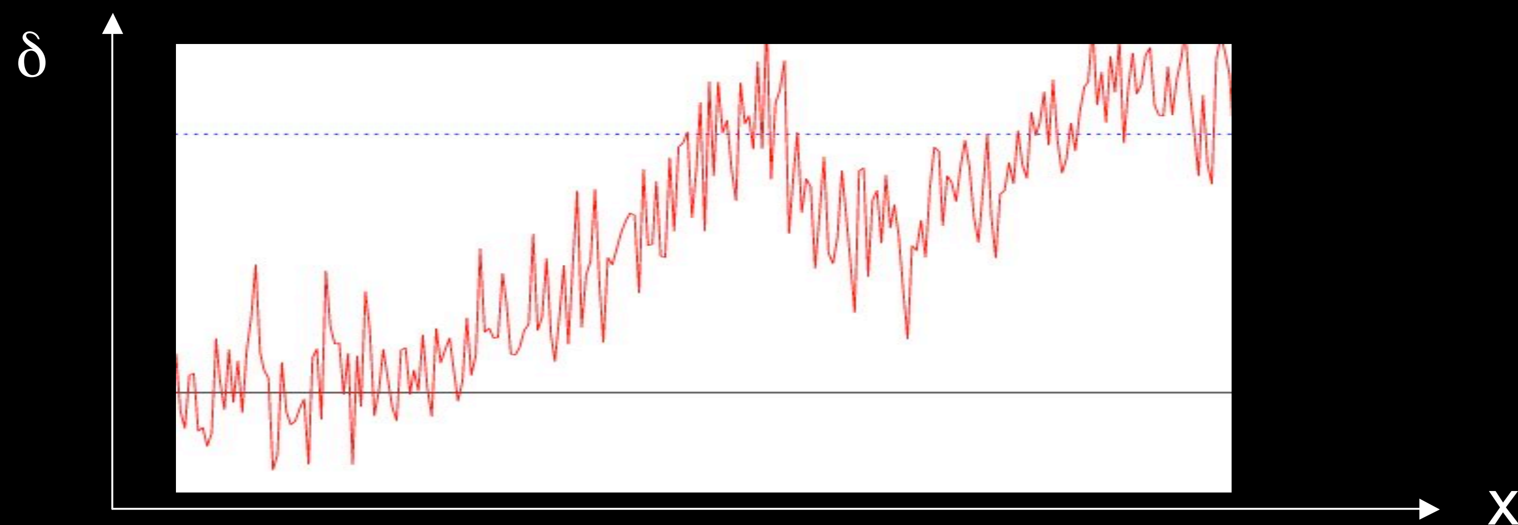
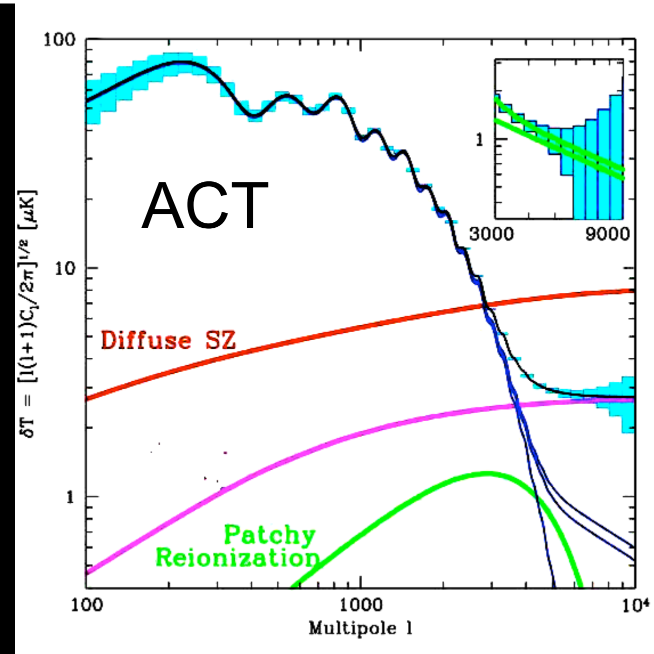


Beware of systematics! "What's the mass of that cluster?"

Very near future:
Atacama Cosmology telescope,

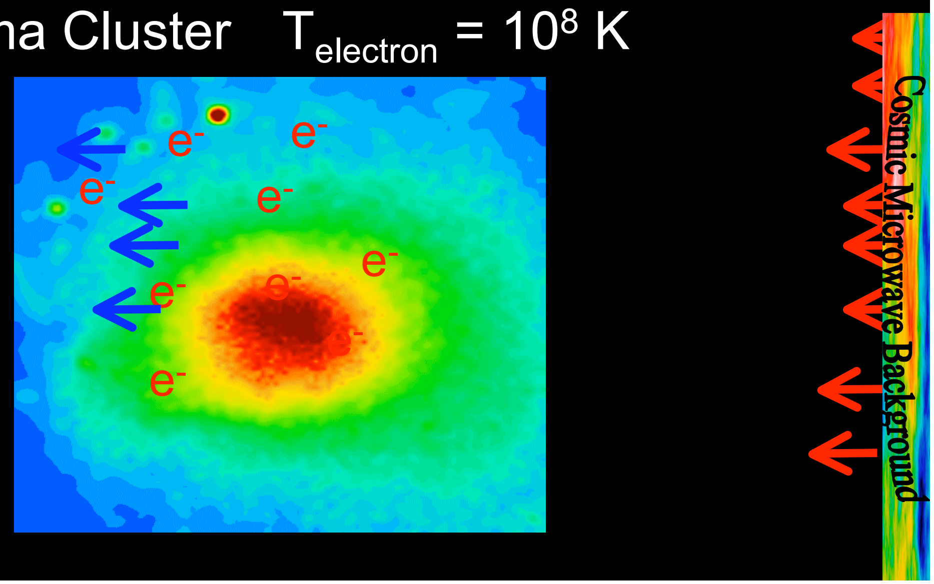
South Pole telescope & Planck



High resolution map of the CMB

Use the CMB as a background light to "illuminate" the growth of foreground cosmological structures

Coma Cluster $T_{electron} = 10^8$ K

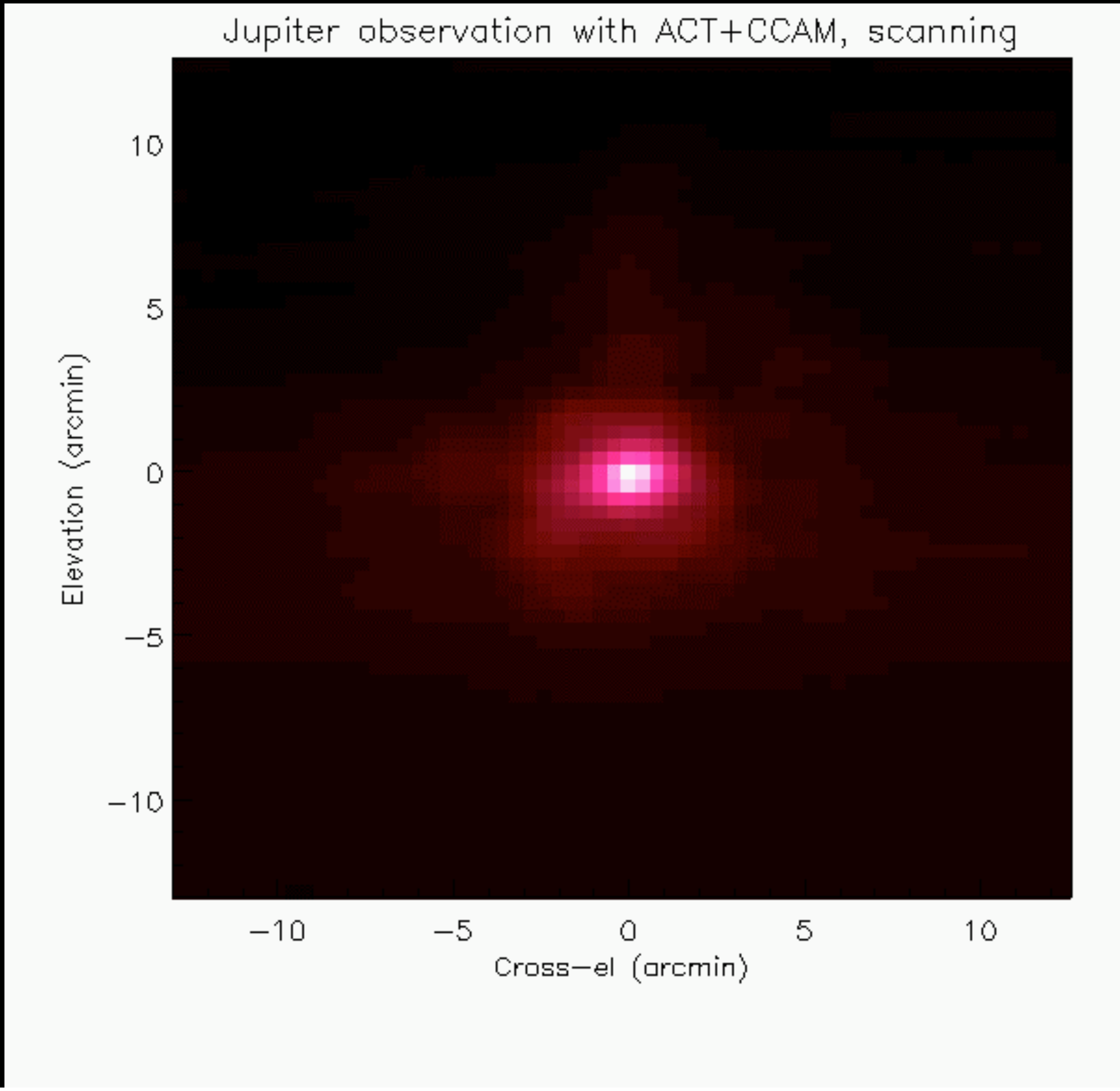


Thermal Sunyaev-Zeldovich

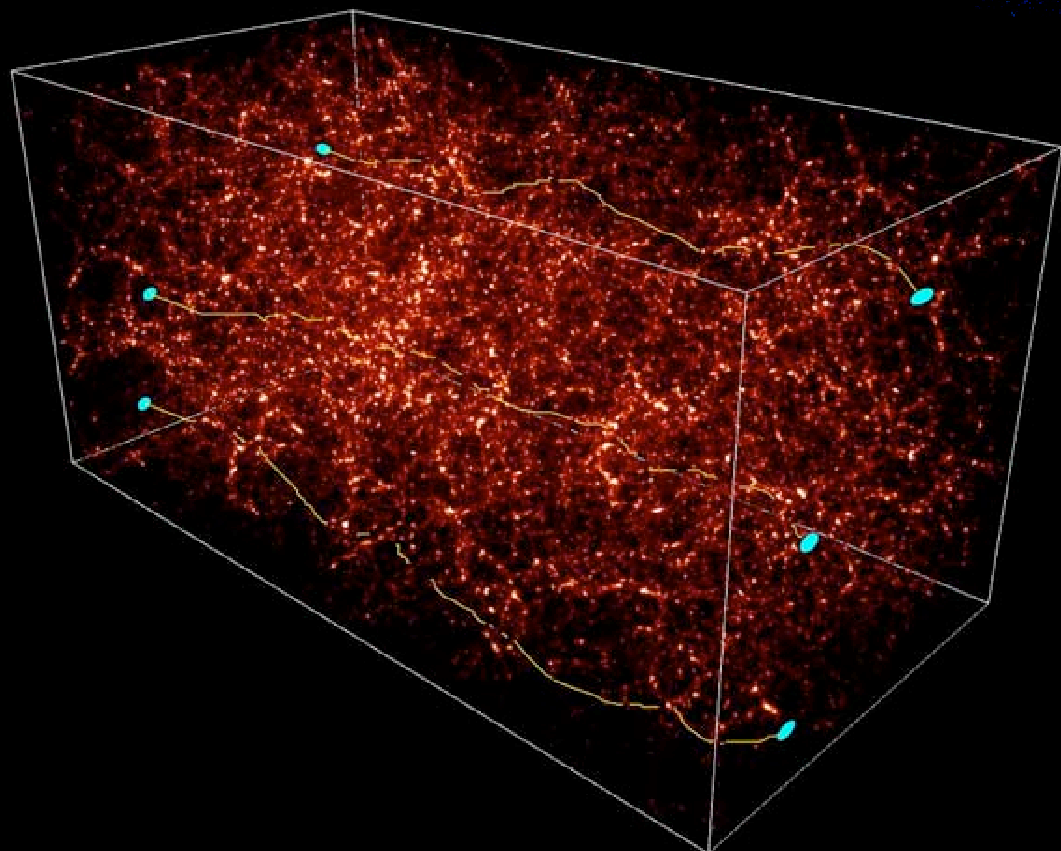
Kinetic SZ

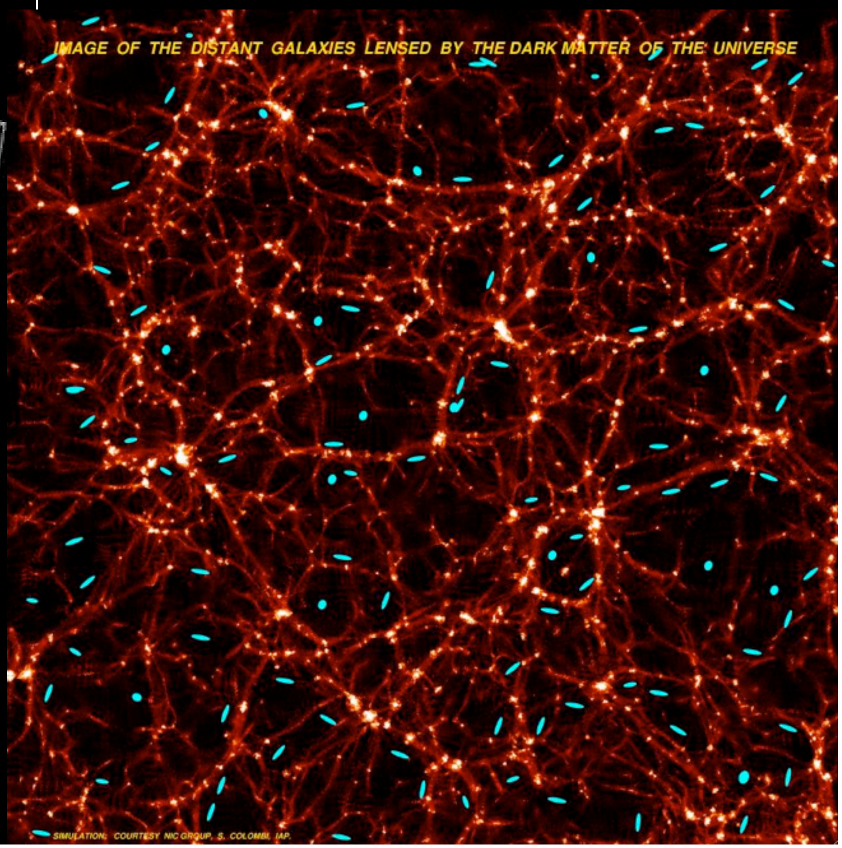
CMB gravitational Lensing

Atacama Cosmology Telescope:
http://www.physics.princeton.edu/act/
first light image



Weak lensing





Need accurate images of many many galaxies at z>1 and their redshift distribution (at least)

Present status

Survey	Telescope	Sky coverage	n gal arcmin^{-2}	Mag	σ_8 ($\Omega_m = 0.3$)	w_0	Ref.
VLT-Descart	VLT	0.65 deg^2	21	$I_{AB} = 24.5$	1.05±0.05		Maoli et al. 2001
Groth Strip	HST/WFPC2	0.05 deg^2	23	I=26	$0.90^{+0.25}_{-0.30}$		Rhodes et al. 2001
MDS	HST/WFPC2	0.36 deg^2	23	I=27	0.94±0.17		Réfrégier et al. 2002
RCS	CFHT CTIO	16.4 deg^2+ 7.6 deg^2	9	R=24	$0.81^{+0.14}_{-0.19}$		Hoekstra et al. 2002a
Virmos-Descart	CFHT	8.5 deg^2	15	I_{AB}=24.5	0.98 ±0.06	-	van Waerbeke et al. 2002
RCS	CFHT CTIO	45.4 deg^2+ 7.6 deg^2	9	R=24	$0.87^{+0.09}_{-0.12}$		Hoekstra et al. 2002b
COMBO-17	2.2m	1.25 deg^2	32	R=24.0	0.72 ±0.09		Brown et al. 2003
Keck + WHT	Keck WHT	0.6 deg^2 1.0 deg^2	27.5 15	R=25.8 R=23.5	0.93 ±0.13		Bacon et al. 2003
CTIO	CTIO	75 deg^2	7.5	R=23	$0.71^{+0.06}_{-0.08}$		Jarvis et al. 2003
SUBARU	SUBARU	2.1 deg^2	32	R=25.2	$0.78^{+0.55}_{-0.25}$		Hamana et al. 2003
COMBO-17	2.2m	1.25 deg^2	R	R=24.0	0.67 ±0.10		Heymans et al. 2004
FIRST	VLA	10000 deg^2	0.01	1 mJy	1.0 ±0.2		Chang et al. 2004
GEMS	HST/ ACS	0.22 deg^2	60	I=27.1	0.68 ±0.13		Heymans et al. 2005
WHT + COMBO-17	WHT 2.2m	4.0 deg^2 + 1.25 deg^2	15 32	R_{AB}=25.8 R=24.0	1.02 ±0.15		Massey et al. 2005
Virmos-Descart	CFHT	8.5 deg^2	12.5	I_{AB}=24.5	0.83 ±0.07	-	van Waerbeke et al. 2005
CTIO	CTIO	75 deg^2	7.5	R=23	$0.71^{+0.06}_{-0.08}$	$-0.89^{+0.16}_{-0.21}$	Jarvis et al. 2006
CFHTLS Deep+ Wide	CFHT	2.1 deg^2 + 22 deg^2	22 13	i_{AB}=25.5 i_{AB}=24.5	0.89 ±0.06 0.86 ±0.05	≤ -0.80	Semboloni et al. 2006a Hoekstra et al. 2006
GaBoDS	2.2m	15 deg^2	12.5	R=24.5	0.80 ±0.10	-	Hetterscheidt et al. 2006
ACS parallel + GEMS+GOODS	HST/STIS HST/ACS	0.018 deg^2 0.027 deg^2	63 96	R=27.0 ? V=27.0	$0.52^{+0.13}_{-0.17}$		Schrabback et al. 2006

“detect potentially hazardous objects in the Solar System. But the wide-field, repetitive nature of the Pan-STARRS observations makes them ideal for a host of other astronomical purposes, ranging from Solar System astronomy to cosmology.

Panoramic Survey Telescope & Rapid Response System

(US air force, University of Hawii, & partners)

Ground based, 4, 1.8 m telescopes (only 1 to begin)

Each night 6000 square degrees one filter.
Plans for 4 filters eventually.

On - going

Survey	Telescope/ Instrument	Sky coverage	Filters	Depth	Period	Main goals
Deep Lens Survey	Mayall+ Blanco	7×4 deg^2	BVRz'	R=25.	2001-2005	WL DE, Clusters High-z Univ.
CFHTLS Deep	CFHT/ Megacam	4×1 deg^2	ugriz	i_{AB}=27	2003-2008	$0.3 < z < 1.$ SNIa DE Clusters, P(k) WL ($z < 2.0$) High-z Univ.
CFHTLS Wide	CFHT/ Megacam	3×50 deg^2	ugriz	i_{AB}=24.5	2003- 2008	WL ($z < 1$), DE, P(k), Bias
SDSS-II SN Survey	APO	250 deg^2	ugriz	r'=22.	2005-2008	$0.1 < z < 0.3 <$ SNIa DE
SUPRIME-33	SUBARU/ Suprime	33 deg^2	R	R=26	2003-?	WL ($z < 1.$), DE, P(k), Bias High-z Univ.
RCS2	CFHT/ Megacam	1000 deg^2	grz	$i_{AB} \simeq 22.5$	2003-?	WL ($z < 0.6$), DE, P(k), Clusters, Bias
CTIO-LS	CTIO	$12\times$ 2.5 deg^2	R	R=23	2002-2006	WL ($z < 0.6$)
COSMOS	HST/ACS	1×2 deg^2	I	I_{AB}=25.5	2003-?	WL ($z < 1$), DE, P(k), Clusters, Bias

Dark Energy Survey: DES (NOAO, NSF, Fermilab, DoE ....)

Ground based, 4 m telescope,
4 bands Photometry 5000 sq deg and repeated 40 sq degrees;
300M galaxies z<1 (ETA: 2008-2012)

Blanco 4m on Cerro Tololo

Image credit: Roger Smith/NOAO/AURA/NSF

Photometric redshifts for SPT and ACT.
Weak lensing

Funded surveys:

Survey	Telescope/ Instrument	Sky coverage	Filters	Depth	Period	Main goals
KIDS-Wide	VST/ Omegacam	1500 deg^2	ugriz	i_{AB}=22.9	2006-2009	WL ($z < 0.6$), DE, P(k), Bias High-z Univ.
UKIDSS-Large	UKIRT/ WFCam	4000 deg^2	YJHK	K=18.4	2006-2012	Clusters $z > 7$ Univ.
UKIDSS-Deep	UKIRT WFCam	3×10 deg^2	JK	K=21	2006-2012	Clusters High-z Univ.
UKIDSS-Ultra Deep	UKIRT WFCam	0.77 deg^2	JHK	K=25	2006-2012	Gal. Formation
WIRCam Deep Survey(CFHTLS)	CFHT/ WIRCam	4×0.75 deg^2	J/H/K	K_{AB}=23.6	2005-2008	High-z Univ. Clusters, P(k)
VISTA-Wide	VISTA	5000 deg^2	JHK	K=20.5	2006-2018	
VISTA-Deep	VISTA	250 deg^2	JHK	K=21.5	2006-2018	
VISTA-VeryDeep	VISTA	25 deg^2	JHK	K=22.5	2006-2018	
PanSTARRS	MaunaKea TBD	$\sim$30000 deg^2	giz	i_{AB}=24.	2008- 2012?	WL ($z < 0.7$), DE, P(k), Bias

Ground based, 8.4 m, all available sky every three nights

Weak lensing (but also, SN, variability, NEA, kuiper belts etc..)

Supernova acceleration probe

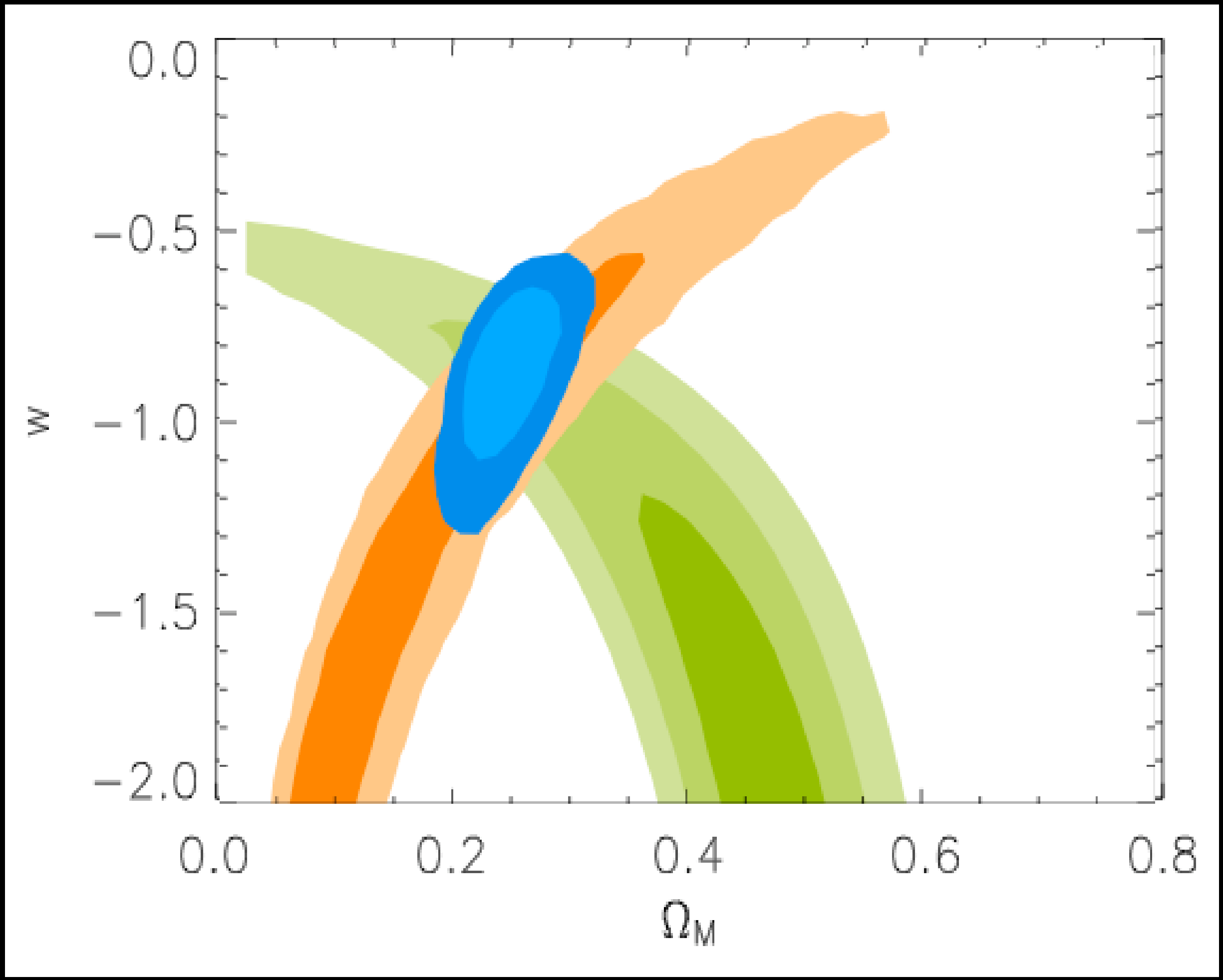
Space based, 2m telescope, started for SN but now lensing

3 filters, 1000 sq deg.

Planned surveys

Survey	Telescope/ Instrument	Sky coverage	Filters	Depth	Period	Main goals
VIKING	VISTA/	1500 deg^2	zYJHK	i_{AB}=22.9	2007-2010	WL ($z < 0.6$), DE, P(k), Bias High-z Univ.
Dark Energy Survey	CTIO DECam	5000 deg^2	griz	i_{AB}=24.5	2009-2014	WL ($z < 0.8$), DE, P(k),
DarkCam	VISTA	~10,000 deg^2	ugriz	i_{AB}=24.	2010-2014	WL ($z < 0.7$), DE, P(k),
HyperCam	SUBARU/ Suprime	~3500 deg^2	Vis.	?	>2012?	WL ($z < 2$), DE, P(k),
SNAP/JDEM	Space	100/1000/ deg^2 5000 deg^2	Vis.+NIR	-	>2013	WL ($z < 1.5$), DE, P(k), SNIa, Bias
DUNE	Space	~20000 deg^2	ugriz+NIR?	i=25.5	~2015?	WL ($z < 1$), SNIa, DE, P(k),
LSST	Ground TBD	20000 deg^2	ugrizy	i_{AB}=26.5	>2014	WL ($z < 2.$), DE, P(k)
Dome-C	SouthPole	? deg^2	?	?	~2012?	SNIa, DE

Dark energy so far...



2dfGRS

H prior

WMAPII

SN

With DE clustering

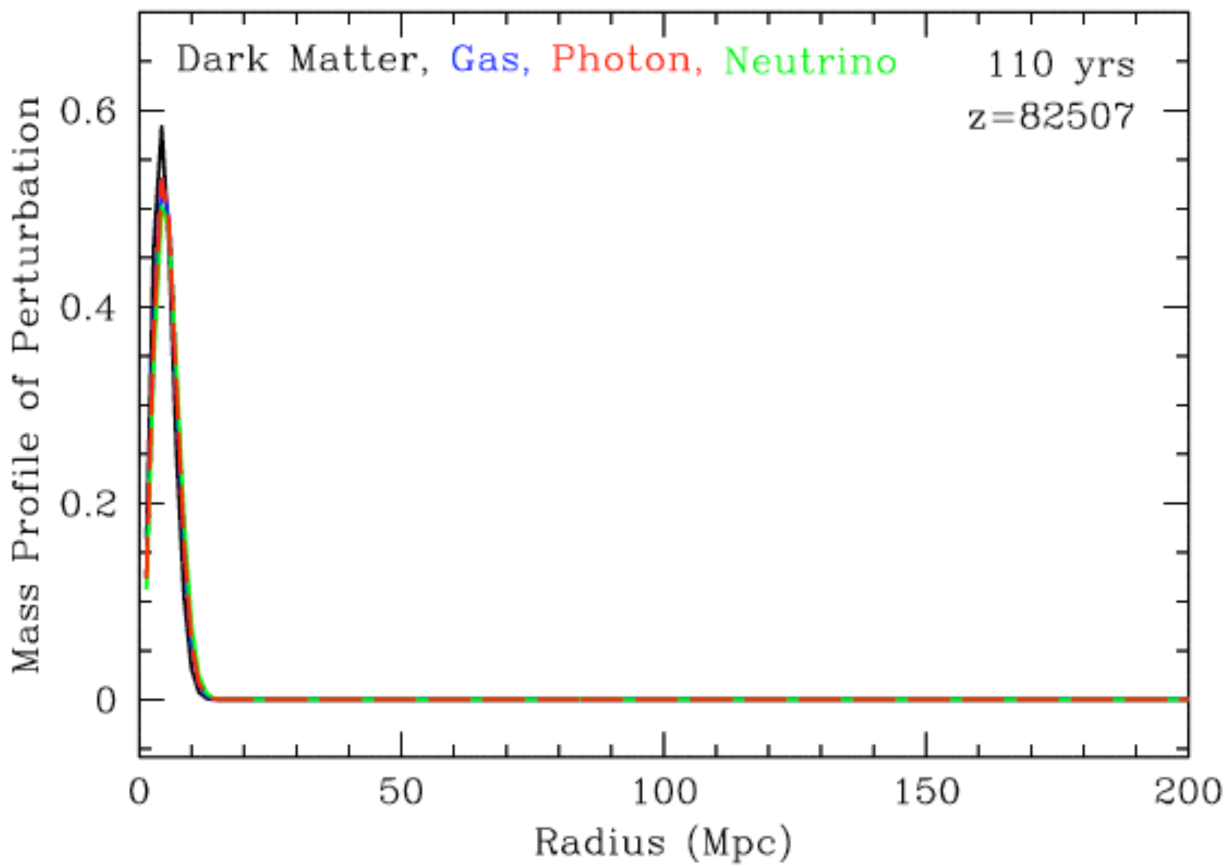
Why so weak dark energy constraints from CMB?

The limitation of the CMB in constraining dark energy is that the CMB is located at z=1090.

We need to look at the expansion history
(I.e. at least two snapshots of the Universe)

What if one could see the peaks pattern also at lower redshifts?

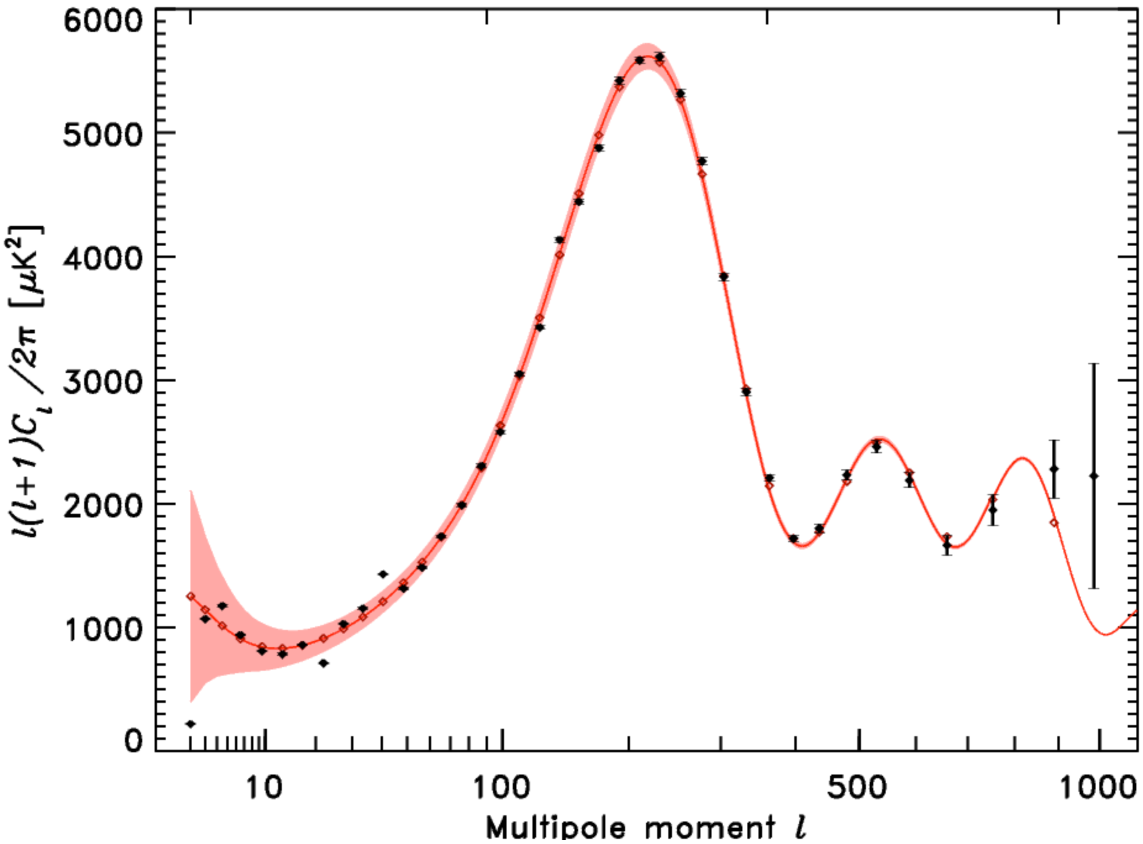
Baryonic Acoustic Oscillations

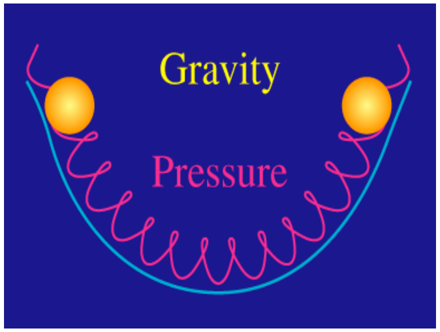


Evolution of a single perturbation,
Imagine a superposition

For those of you who think in Real space

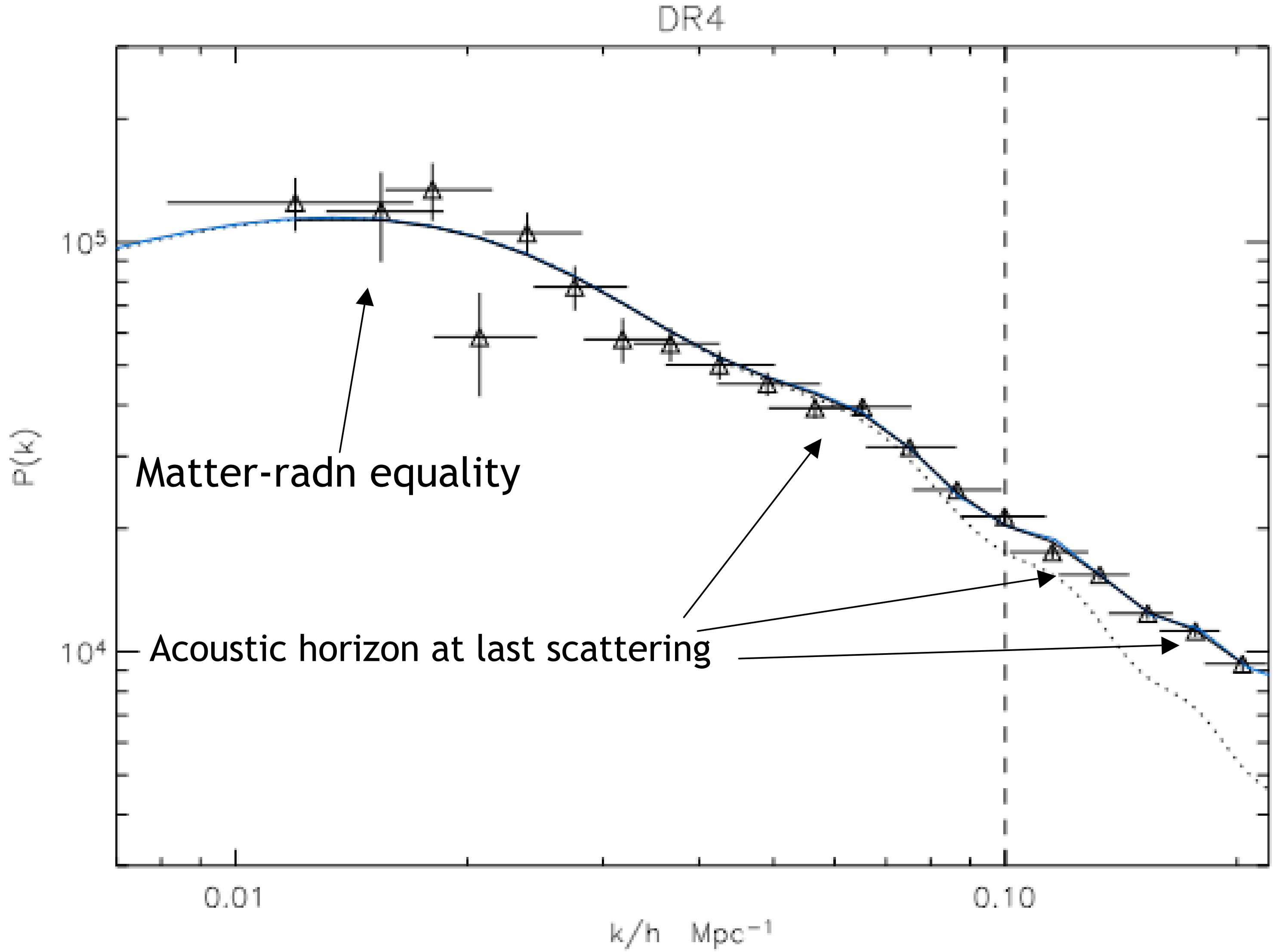
Courtesy of D. Eisenstein



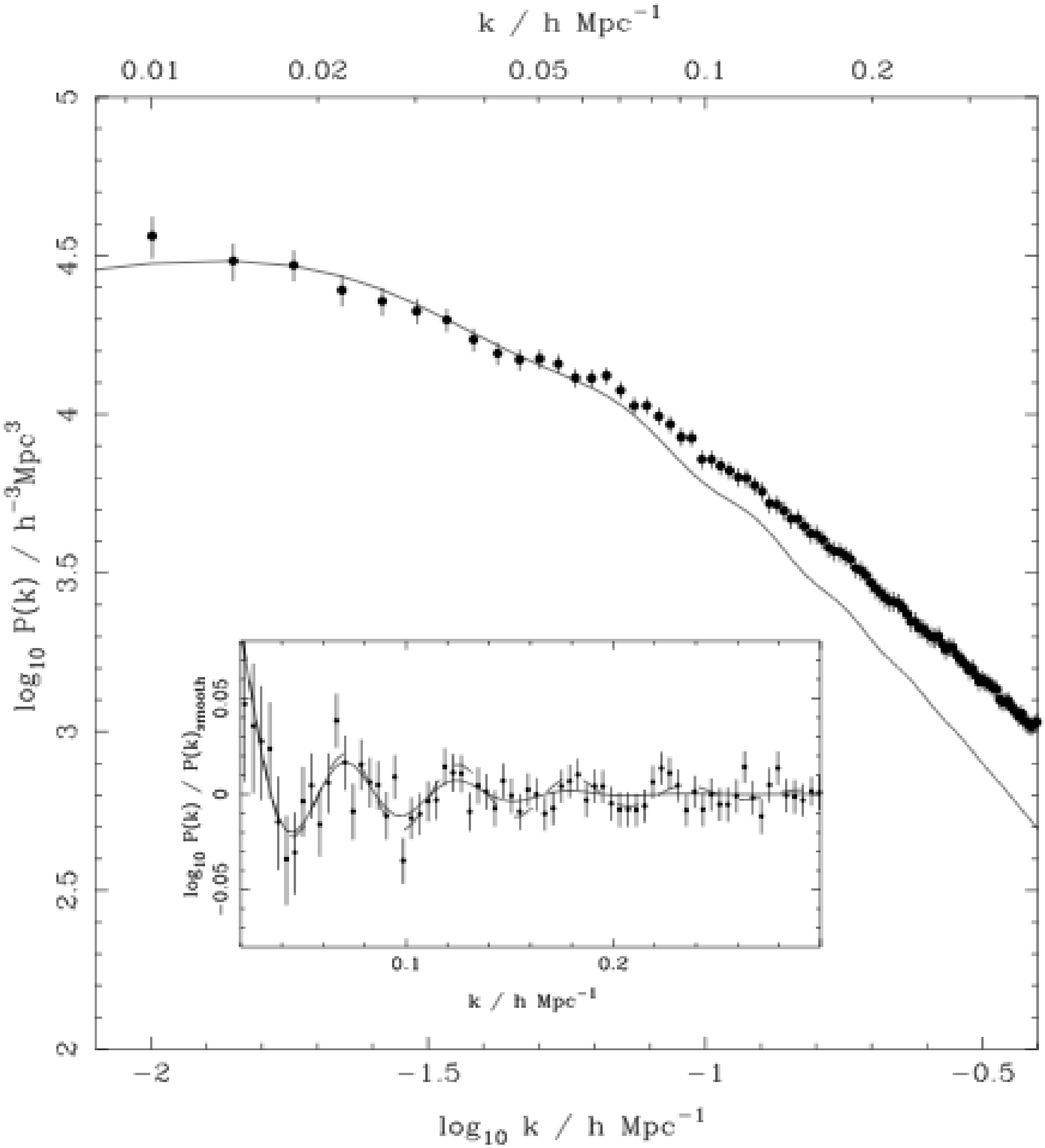


If baryons are ~1/6 of the dark matter these baryonic oscillations should leave some imprint in the dark matter distribution

Fore those of you who think in Fourier space



Data from Tegmark et al 2006



DR5

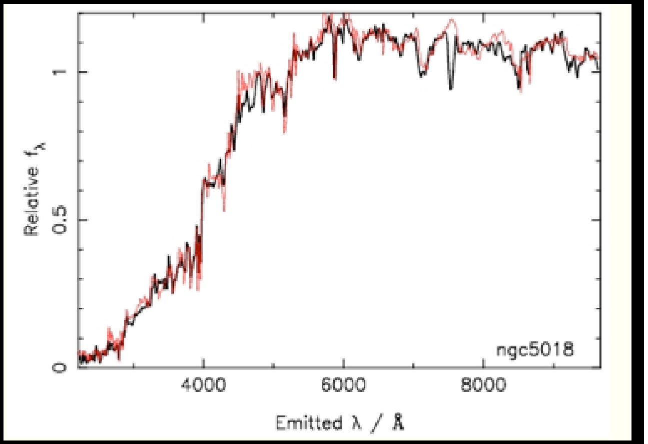
from Percival et al 2006

Robust and insensitive to many systematics

Spectroscopy or photometry?

AAOmega 600K galaxies, z~1
(10% error on w)

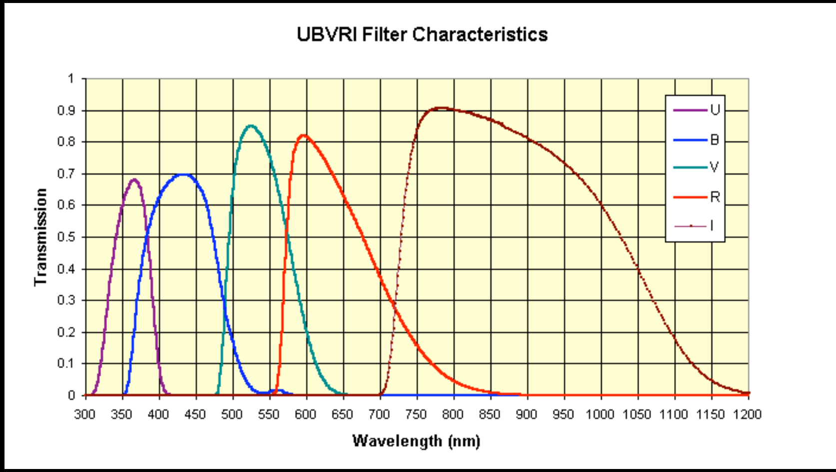
WFMOS several million galaxies >2012



VISTA, DES, LSST

Degrade information in the z direction but is faster & can cover more sky

Could do weak lensing almost for free



The debate is still open!

PAU-BAO

Close collaboration between particle physicists (theorists and experimentalists) and astrophysicists (theorists and observers)

Awarded consolider-ingenio 2010, E. Fernandez, PI

"Hybrid" technique: narrow band photometry (the best of both worlds?)

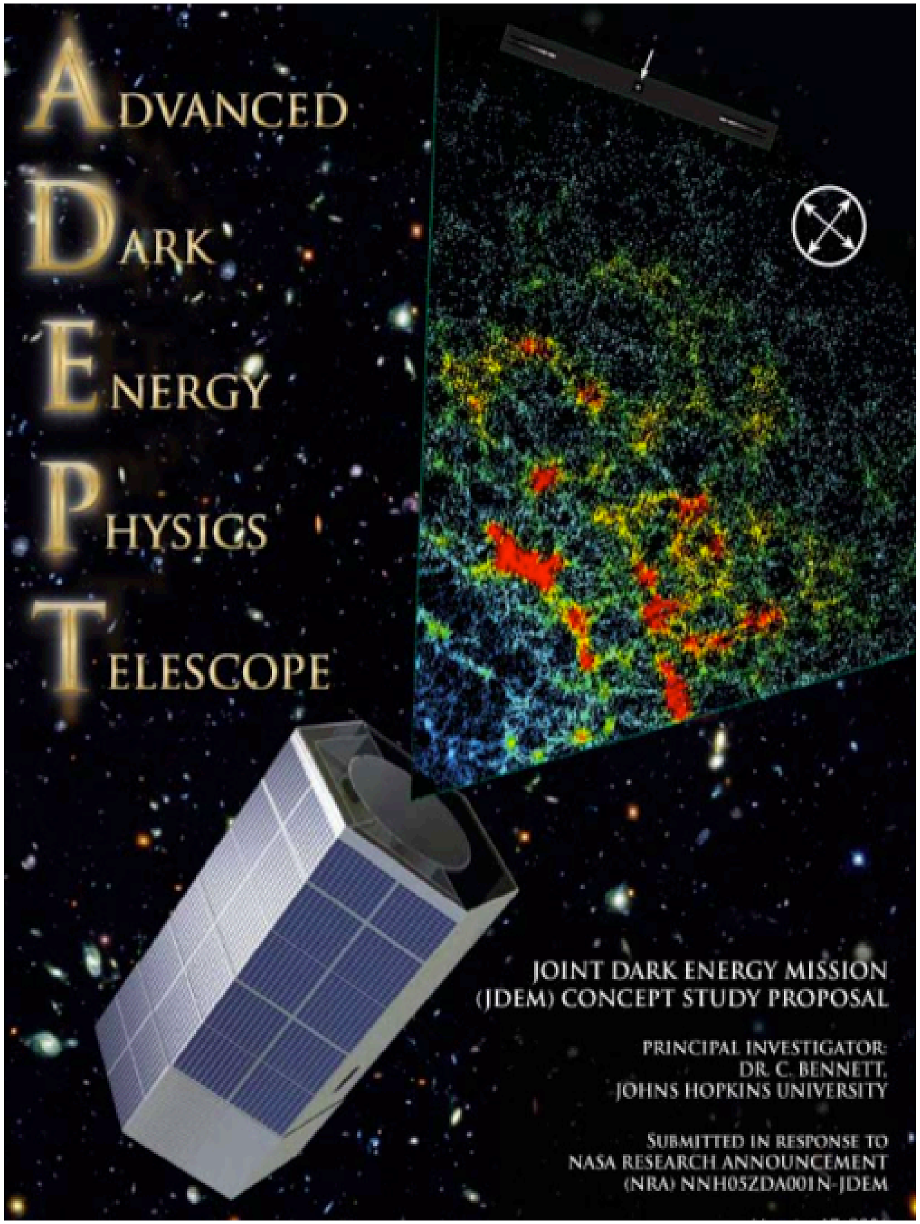
Survey ~10000 deg^2 $0.1<z<0.9$, ~40M galaxies

Likely: dedicated telescope. New camera

Measures both H(z) and Da

Instituto de fisica de alta energias (IFAE-Barcelona)
Instituto de ciencias del Espacio (ICE-Barcelona)
Instituto astrofisico de Andalucia (IAA-Granada)
Instituto de fisica teorica (IFT-Madrid)
Centro de investigaciones[…] (CIEMAT-Madrid)
Instituto de fisica corpuscolar (IFIC -Valencia)
Puerto de informacion Cientifica(PIC-Barcelona)

The ultimate survey for Baryon oscillations,
complementary to ground based approaches



(C. Bennett PI)

100M galaxy redshifts (and positions)

$1<z<2$ Volume $100(\mathrm{Gpc}/h)^3$

1000's SN 1A at $0.8<z<1.3$
(no need for follow up)

Measures both H(z) and Da

Conclusions

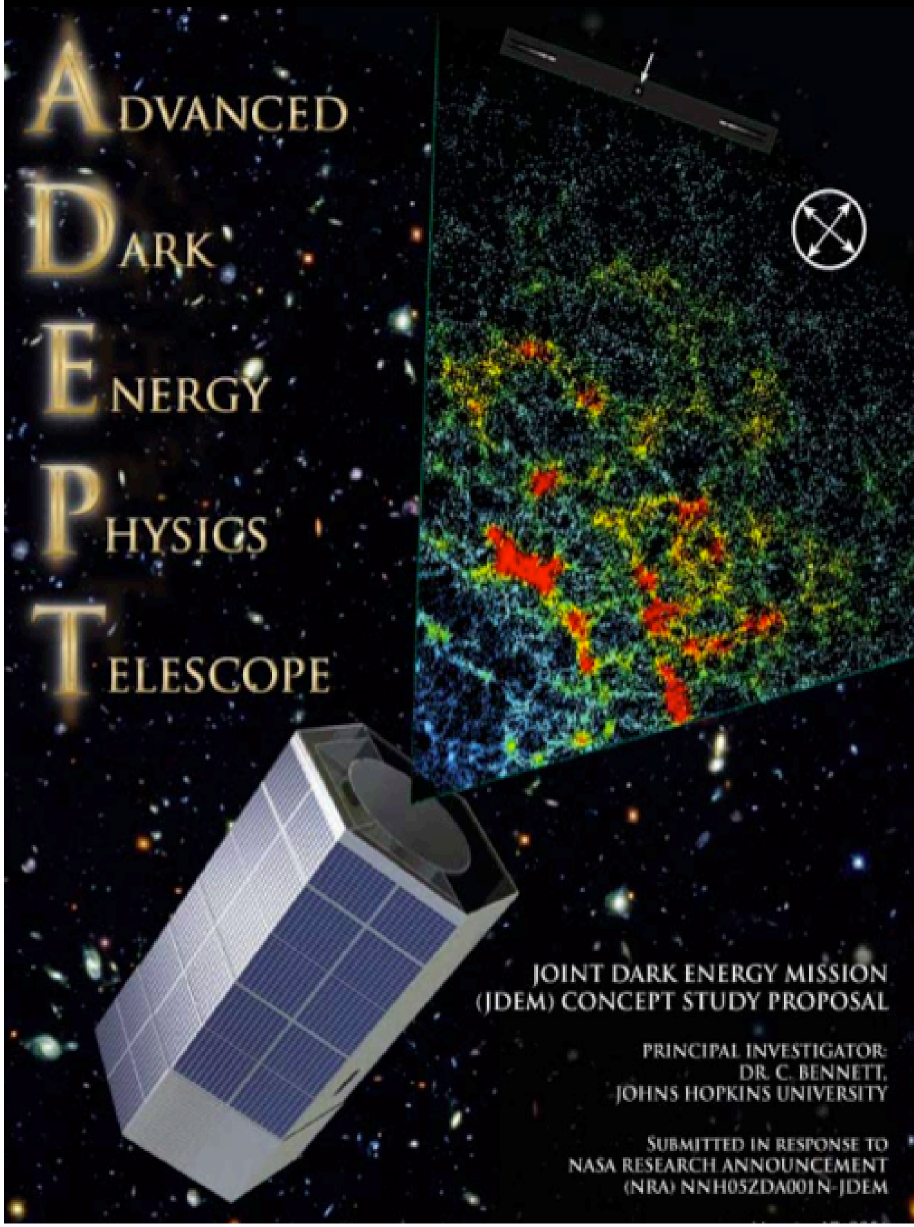
The standard cosmological model is extremely successful,
but leaves us with 2 fundamental problems:
-Nothing weighs something (and gives accelerated expansion,
- but not as much as "naively" expected)
-Is our theory of gravity and particles correct or complete?
-Something like that may have happened before (inflation)
-Is the physics related? And what is it?
-Has inflation acted as a magnifying glass and
microscopic effects left their signature in the sky?

Expect an avalanche of data (and of acronyms!)

LSST SNAP PAU Pan-Starr BPol BOSS WFMOS DES
JDEM ADEPT DUNE CMBPol QUIET Spider

Cosmology is far from "solved"....

ADEPT Science Team



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weak lensing
baryon acoustic oscillations
supernovae
galaxies

[5]high energy physics
[6]data analysis
[7]space flight hardware
[8]cosmology